In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institute shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

7/25/68

TRAFFIC ON A TWO-LANE TWO-WAY RURAL ROAD

A THESIS

Presented to

The Faculty of the Graduate Division

by

Joel Norman Banks

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Industrial Engineering

Georgia Institute of Technology

March, 1969

TRAFFIC ON A TWO-LANE TWO-WAY RURAL ROAD

Approved:

Chairman

Date approved by Chairman: 9 MAY 69

ACKNOWLEDGMENTS

I would like to express my appreciation to Dr. Paul H. Wright of the School of Civil Engineering for serving as my thesis advisor. Dr. Wright contributed to this research his extensive experience and knowledge of traffic flow systems and took an active part in encouraging the research effort.

Also, I wish to thank Dr. William W. Hines and Dr. Jack Walker of the School of Industrial Engineering for serving on my reading committee. Their comments and criticisms were well taken, and they helped to organize the research into a proper format.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

SUMMARY

The understanding of highway traffic flow has become increasingly important during the last decade. Theorists have dealt, generally, with only limited situations, for which abstract models have been derived. The main shortcoming of these studies is their failure to consider the systems nature of traffic flow. The objective of the present research is to develop a better understanding of certain traffic flow characteristics, such as platooning, passing, flow rate, and average speed, within a systems context.

The system studied in this research is a two-lane, two-way rural road, of finite length seven miles. The system was modeled by a set of logical statements and equations, and the model was simulated by transforming these equations into the ALGOL computer language. The resultant program was run on the Univac 1108 computer.

The primary exogeneous variables were the arrival headway distribution, the opposing headway distribution, and the desired speed distribution. It was found that both passing and platooning decrease as stream mean speed increases. A flow concentration curve was also defined. This curve was similar in shape to curves obtained by other investigators and showed that the maximum flow rate is achieved for intermediate densities.

To validate the model, a field study was made in which the values of the aforementioned variables, as well as the actual speed distribution, were determined. The simulation results showed close agreement for actual speed per desired speed category.

CHAPTER I

INTRODUCTION

Objectives

This study is concerned with the nature of traffic flow on the two-lane two-way rural highway. The primary objective of this study is to gain an understanding of the nature of the effects of traffic volume and desired speed on traffic flow rate, realized speed, amount of passing, and on amount of platooning.* A secondary objective is to gain an understanding of the relationship between the distribution of headways** at one point on the road to the distribution of headways at a point farther down the road.

Importance of Problem

The problem of planning highways for heavy and increasing traffic flow has become highly complex, and it has received active study. More complete information on the nature of the effects and interactions of traffic variables is needed in order to effectively design highways of the future.

The manner in which traffic engineers have attempted to deal

---

*Two cars are platooned when the following car is so close to the lead car that the following car must either initiate a pass or must track the lead car (see Chapter III).

**The headway is defined as the time interval (seconds) between successive cars.

with the traffic problem, and the approaches made by traffic flow theorists, represents two extremes in the method of solution. Traffic engineers have relied mainly on empirical studies, semi-empirical models, and general rules of thumb. They have been slow to adopt the findings of the traffic flow theorists who have, on the other hand, attempted to describe traffic phenomena in purely analytical terms. Traffic flow theorists have created mathematical models of limited situations. The equations they derive deal with microscopic situations which are related in a very abstract way to real traffic systems. By failing to treat the traffic system in macroscopic terms, the theorists have been unable to present a unified treatment of complex traffic flow systems.

Scope of Study

This study is concerned with the traffic flow characteristics for a single road. Although a single road is usually a component of a larger network, the road-network interaction was not considered in this study. However, a dynamic approach will be made to more completely understand how the two lanes of traffic interact and, generally, to find which traffic variables are the most important determinants of flow characteristics.

Assumptions and Limitations

To set the system within a context amenable to study, several assumptions were made. The assumptions are as follows:

1. The road length is chosen to be seven miles.
2. Flow into and out of the system may occur only at the seven

mile boundaries, i.e., no side roads exist.

3. Car arrivals follow a Poisson process, i.e., arrival headways are exponentially distributed.

4. Desired or "free" speeds are normally distributed with parameters μ and σ^2.

5. Passing is permitted, subject to certain restrictions.*

6. Flow conditions in the opposing lane are related in a direct way to those in the primary lane of consideration (mainstream).

7. Since the system is initially empty, the statistics generated can be considered to relate to the system during the transient period only. No inference may be drawn about steady state behavior.

Method of Approach

Because the system to be studied involves the complex interaction of many vehicles, a dynamic approach was called for. Since detailed information about the system components was available, it was decided to analyze the system by use of simulation. The scope and complexity of the problem and the need for repeated performance and recording of calculations dictated that this simulation be performed with the aid of a computer.

Many simulation languages were available, including DYNAMO, which is applicable to systems where continuous flows and levels are involved, GPSS-II, which is designed to handle unit discrete flows, SIMSCRIPT, SIMULA, and others. A study of these languages indicated that none

---

*These restrictions are outlined in Chapter III.

offered the flexibility needed to adequately represent the present system. To provide this flexibility, the ALGOL language, as modified for the Univac 1108 computer, was selected for use in this research.

CHAPTER II

LITERATURE STUDY

Background Information

Most of the traffic research now being done, especially in the academic area, involves the creation of a traffic model. A traffic model is "... any system, whether physical or abstract, whose behavior can be observed or calculated and is related to traffic in some useful way."(8) Although physical models have been proposed, they have not as yet been used to describe traffic systems. Basically, three different approaches have been used to model traffic:

1. Considering traffic phenomena as chance realizations of events from given distributions and deriving, by statistical means, system quantities of interest.

2. Considering traffic flow on a highway to be analogous to the flow of liquid through a medium. Equations for the former are readily obtained from those already derived for the latter.

3. Incorporating knowledge of the components of traffic flow into a dynamic model by use of computer simulation.

The first technique has had wide application where quantities such as mean values, queues, etc. are the main concern. The second technique is applicable to dense flow conditions and has brought about such concepts as the bottleneck and the shock wave. The third technique is applicable to a broad base of problems and is used, generally, when the system is too complex to model otherwise.

The results of empirical studies and other research have provided insight into the traffic problem. It is generally agreed that speed and density are the most important measures of traffic flow. As traffic density is increased beyond a certain value, the speeds are reduced to such an extent that the total flow is decreased. However, the relationships between speed and flow and between density and flow are not linear. Rather, it is proposed that the flow-density and the speed-flow relationships are of the nature depicted in Figures 1 and 2.

As seen in Figure 1, when density k is zero, there is no flow. As density increases, the flow rate increases because the increase in density more than offsets the reduction from free speeds. However, as density increases past k_m, further increases in density cause a disproportionate reduction of speed, thereby reducing the flow rate. As density approaches k_j, the jam density, speeds approach zero.

Whenever differences in speed from one traffic subsystem to another occur, traffic will accumulate in the lower speed subsystem while it is being fed by higher speed traffic upstream to the location, unless cars can pass at will. Vehicles in one lane of traffic have little choice of speed, since each vehicle influences the speed of the vehicle following, for the high volume case. An incident is quickly transmitted up the traffic stream in the form of a wave of speed change (8).

The term congestion could be used to indicate a reduction from

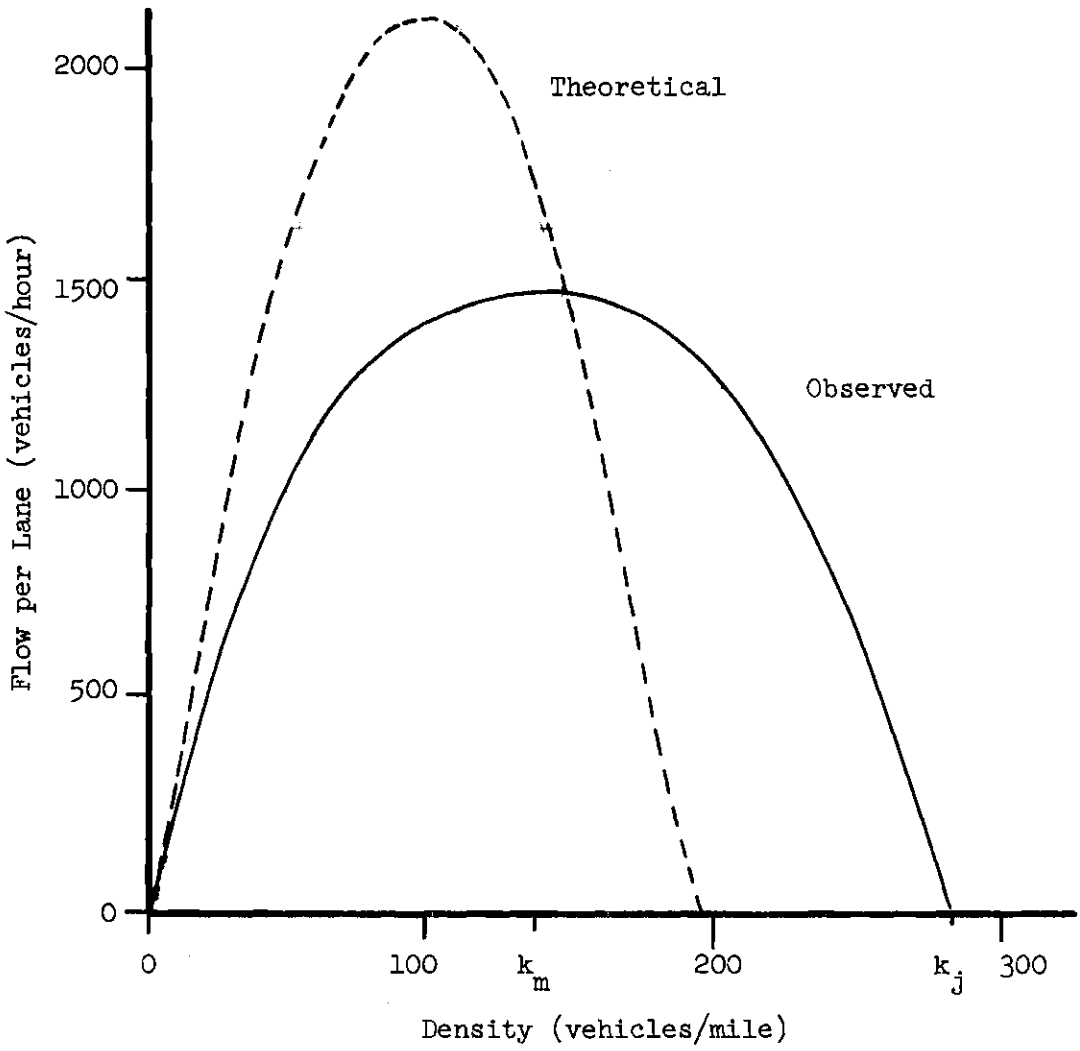

Figure 1. Flow-Concentration Curve per Lane of Traffic (Greenshields, 1954)

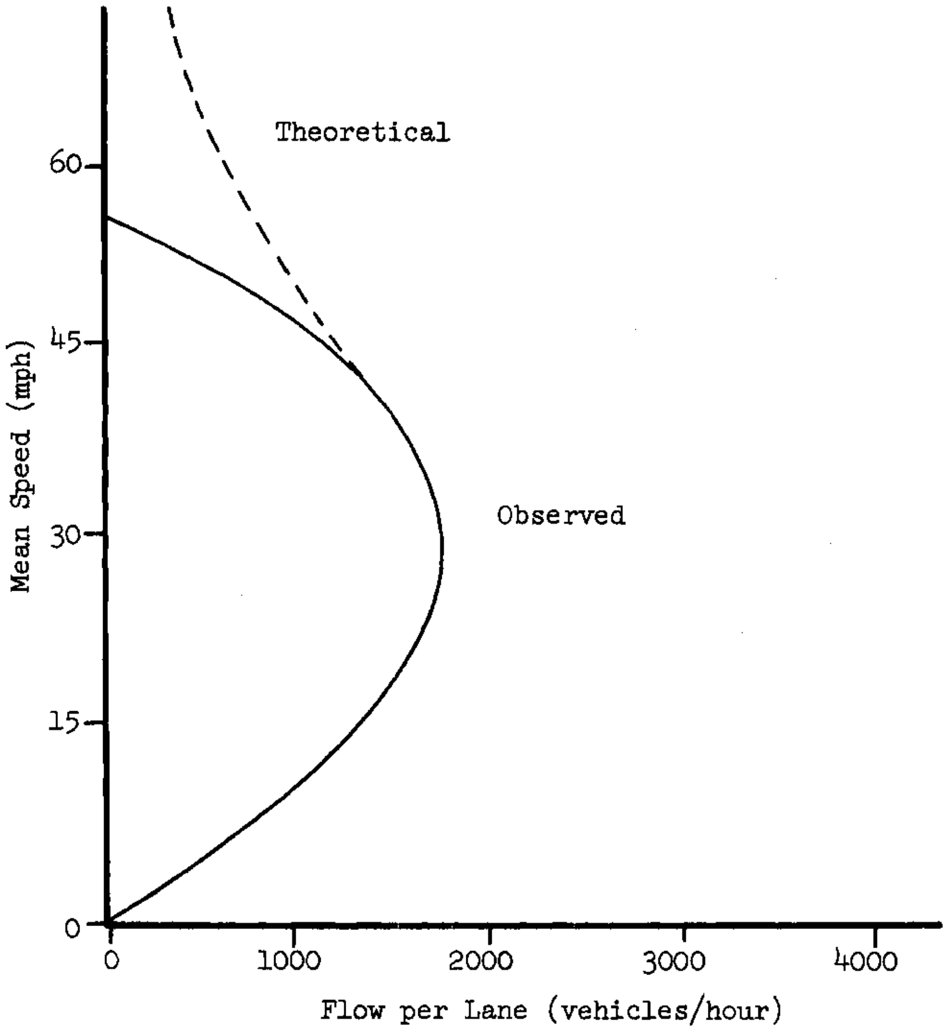

Figure 2. Speed-Flow Relationship for One Lane

the maximum flow attainable at some level of free, or desired, speed. The maximum flow is not usually attained because some drivers select different speeds and hence, headways, than the ideal ones. As speeds decrease and volume increases, the need arises for more frequent passing, but this in turn is a decreasing possibility as more and more lane space is permanently occupied (14).

Published Studies

Not unexpectedly, many papers have been written on the flow of traffic on two-lane roadways. Both simulation and analytical approaches are to be found in the literature. These approaches will be highlighted in the remainder of this chapter.

As early as 1941, the Public Roads Administration had conducted field studies of vehicle-passing practices on two-lane roads (21). The result of these studies was a set of empirical data concerning various phases of the passing maneuver, for different values of passing speeds. A pass was classified according to the manner in which the passing vehicle was affected by the opposing traffic. The results of these studies are summarized in Ritter and Paquette's Highway Engineering (24).

Although some work was begun at an early date, the largest volume of work which has been done in the area of traffic flow theory has been done over the last decade.

In 1966, Warnshuis (27) made a simulation study of two-way traffic on a two-lane road. In this study, flow on a road of infinite length was approximated by creating a circular track of finite length. Also, the set of cars traveling in each direction remained fixed. A car traveled at its own desired speed unless the car was following or passing another car. In this model, platooned vehicles must maintain uniform intercar spacing unless the car behind the leader executes a pass, or unless one of the cars in the platoon decelerates. It was found that the relationship between average speed and mean desired speed is largely insensitive to changes in the distribution of desired speed, for a given mean speed, but very sensitive to traffic density. The resulting distribution of platoon sizes was also shown. No field study data were used to validate the study.

The basic assumptions used by Warnshuis are very much like the ones adopted for the present research. However, some of the rules to be used for the current study are quite different. For example, unlike Warnshuis, this model involves a road of finite length on which the number of cars in a lane is not fixed but a function of the system parameters. In the main, the objectives of the present study differ from those of Warnshuis.

Although the literature search revealed no other major simulation study of two-way traffic, many authors have developed mathematical models for certain aspects of traffic flow, such as flow rates, average speed attained, and passing characteristics.

In "A Model for Traffic Flow on a Two-way Rural Highway" (18), Miller attempted to predict the steady state values of certain quantities, such as the distribution of actual speeds as functions of desired speeds, average delays suffered by desired speed categories, and average speed of platoons. His mathematical model has been partially validated by the use of data obtained from the 1965 Highway Capacity Manual and other data later collected. However, Miller's model is applicable only to low density traffic flow conditions. A more dynamic approach is needed for higher densities.

Oliver reports the result of a study of one-way traffic flow on a two-lane road (20). His mathematical model rested on two basic principles: that the total number of vehicles are conserved, and that lane changes are functionally related to the densities in each lane. Oliver obtained a set of non-linear differential equations by use of the above principles and by an accounting system which keeps track of changes of flow rates and densities over time differentials. The model did not include a detailed merging or passing rule; rather, it dealt with aggregate quantities such as density from which equations of continuity were derived. It was shown that the theoretical value of lane changing flow rates agreed fairly well with the field data taken.

In 1965, Erlander presented a mathematical model for traffic on a two-lane road (5). In his model, the road is considered to be infinitely long. He investigated the average speed of vehicles with a given desired speed, where passing of a slower moving vehicle is allowed subject to certain constraints. Erlander developed a non-linear integral equation for the average speeds attained. He then investigated certain aspects of this equation, such as average distances a vehicle must travel at reduced speeds before being able to pass, flow rate, and number of passed per given length of road per hour.

Also in 1965, Gustavsson presented a model for passing on a two-lane road with limited visibility (11). Here, the primary concern was with the decision to pass, which was dependent on the density of on-coming traffic and the sight distance. As in Erlander's paper, the distance between the car to be passed and the next car ahead is not considered. The author derived an autocorrelation function for the proposed sight variation model.

In 1966, Andreassend completed a study of the use of mathematical descriptions to determine overtaking times and distances (1). The overall performance of a car is described by fitting an exponential time-speed relationship to field data. Using this expression, he was able to determine analytically the overtaking times and distances for given car spacings. Also considered were the effects of speed limits and initial differences in speeds between the passing car and the car being passed. Although his analysis is quite interesting, the main value of his study is in the determination of line markings for two-lane roads.

G. F. Yeo (28) determined the theoretical delay of a vehicle wishing to travel at some speed u which is greater than the constant speed which all other vehicles in its lane are assumed to travel. Assuming traffic in the opposing lane to be composed of a series of platoons and gaps, Yeo derived the expected mean speed of the u vehicle in terms of its desired speed, the speed of the other vehicles, and expected waiting times for different situations.

The evaluation of the flow rate or capacity is an important indicator of the safe operation of roads and highways. Associated with this variable is a quantity called the headway, or gap size. Knowledge of the distribution of this variable, then, is of signal importance. In fact, it is possible to consider a lane of traffic as a sequence of moving gaps (22). An excellent presentation of certain gap distributions can be found in a presentation by Buckley (2).

Daou (3) studied flow within platoons and suggested that headway could be expressed as a linear function of velocity. For one-lane flow, he found evidence to support an assumption of a log-normal distribution of headways. He related gap, S, to velocity, u, by the equation

$$S = T \cdot u + L + B \quad \text{(feet)} \tag{2-1}$$

where

T = reaction time (secs)

L = car length (feet)

B = buffer distance (feet)

The headway, T_s, is then

$$T_s = T + (L+B)/u \quad \text{(secs)} \tag{2-2}$$

For the empirical data taken

$$T_s = 1.49 + 35/u \quad \text{(secs)} \tag{2-3}$$

Expressions of capacity have been obtained for various speeds and headways, especially for the situation in which passing is not possible. The general form of the equation given by Hobbs (14) is

$$C = \frac{5280\ V}{H_d} \tag{2-4}$$

where

C = capacity of one lane in cars per hour

V = average speed in mph

H_d = average minimum headway distance in feet

Hobbs' expression for determining H_d is

$$H_d = L + 1.47\ TV + V^2/30f \tag{2-5}$$

where

L = length of vehicle in feet

V = speed in mph

T = reaction time in seconds

f = coefficient of friction

Herman and Potts have been leaders in the development of car-following theories. In one of their papers (13), a general discussion is given of a car-following theory in which the acceleration of a car following another car is proportional to the relative velocity and is implemented after a reaction time T seconds later. The proportionality coefficient may have several forms, namely: constant, step, or one inversely proportional to the intercar spacing. The equations derived deal with the so-called "follow-the-leader" situation, in which passing is not allowed. The general expression for the car following law is

$$\ddot{X}_{n+1} = \alpha\,(\dot{X}_{n+1} - \dot{X}_n) \tag{2-6}$$

where

$\dot{X}_n$ = speed of the n^{th} car at time t

$\ddot{X}_{n+1}$ = acceleration of the $n+1^{st}$ car at the time t + T

α = proportionality coefficient (t^{-1})

The follow-the-leader equation forms which have been hypothesized can be categorized by examining the general expression for α, the proportionality coefficient. The expression for α is usually of the following form

$$\alpha = \frac{\beta\ (\dot{X}_{n+1})^m}{(X_n - X_{n+1})^{\ell}} \tag{2-7}$$

where

$(X_n - X_{n+1})$ is the spacing between the lead and the following car

The term β is a measure of driver sensitivity, typically valued at less than unity. Table 1 gives, for different values of m and ℓ, the principal investigator for the model.

Table 1. Principal Investigators for Various Car-Following Laws

m	ℓ	Principal Investigator
0	1	Herman, et al. (13)
0	2	Greenshield (10)
1	2	Edie (4)

The follow-the-leader theory applies mainly to the fairly dense traffic situations, since interactions between cars very nearly disappear at low volume traffic flow.

Another study by Herman, et al. (12), of the increasing incidence of multi-car pileups showed that accidents caused by rear-end collisions occur in two different ways. In the first, a driver follows the car in front so closely that it is impossible for him to avoid a collision if the car in front quickly decelerates. However, other collisions occur which involve some vehicle which was far behind the one which suddenly changed speed. This type accident usually initiates a multi-car pileup. Analysis of this type accident shows that it is dependent upon the manner in which the initial disturbance is propagated down the line of cars. At different speeds, the amplification of the disturbance will be different. Herman suggested that other variables are: the number of cars in the platoon, the intercar spacings, and the degree of disturbance initiated by the lead car. Driver sensitivity is also important, though difficult to measure objectively. Modeling of the case of disturbance, or "shock wave" propagation, can be of vital importance in understanding the nature of the multiple-car pileup.

Theeden (25) assumed that cars traveled on a road of infinite length. In this mathematical model, cars freely pass each other. Their speeds are generated from a common distribution. Cars were examined at a fixed point from which intercar spacings were generated. He demonstrated that passing, under certain restrictions, followed a general Poisson process.

Hydrodynamic approaches have also been proposed. An analogy is made between the flow of fluids and the movement of vehicular traffic. It has been shown that, as in the case of follow-the-leader theory, the analogies are valid only for the high volume case. Much work in this area has been done by Greenberg (9), Lighthill and Whitham (17), and Richards (22). The results of this work can be partially summarized as follows

$$V = U_s \cdot D \tag{2-8}$$

$$U_s = C \cdot \ln(D_j/D) \tag{2-9}$$

from which

$$V = C \cdot D \cdot \ln(D_j/D) \tag{2-10}$$

where

V = flow rate (vehicles/hr)

U_s = space mean speed (mph)

D = density (vehicles/mile)

D_j = jam density

C = proportionality coefficient

The effect of buses and trucks on the speed of traffic is another topic which has received active study. Although no major study has been done on a rural road, Thorne (26) has made a study of an urban street in England. The space mean speed produced by the presence of buses traveling in the direction being considered was compared with the effect of cars on the same street. This study gave information on the flow rate which could be expected for given concentrations of cars and buses.

As a final topic, mention should be made of work done by Levine (16), who formulated a design principle for linear feedback control of the position and velocity of vehicles within a platoon of high speed vehicles. He made an analog computer validation of his model and showed that the transient response characteristics were stable. This type of approach will probably have application for the proposed automated traffic system of the future.

CHAPTER III

METHOD OF PROCEDURE

The present research involves the modeling and study of traffic flow on a two-lane road. To introduce the method of research used in this study, the general assumptions and operating rules used to model the system will be given. Next, the flow diagram of the system will be given, followed by a detailed explanation of the flow components. Finally, a description will be given of the field study which was undertaken in order to validate the simulation model.

Description of the Model

The general assumptions and operating rules used to model the system are:

1. Each car seeks to maintain its desired speed but obeys logical rules when following other cars.

2. Precedence in passing is given to that car following the platoon leader, in a given platoon.

3. A car may pass only one other car at a time.

4. The logic a driver used in deciding to pass is complex but can be quantitized into several basic components.*

5. Continuous time may be approximated by half second intervals.

---

*See page 26.

On the following page is given the flow diagram for the system. In the explanation which follows, the symbol [ ] will be used to denote a connector, to be used in tracing the steps of the algorithm.

The first event is the arrival of a car. This car is then assigned a desired speed, $\dot{x}$ (feet/second), which is a realization of a random variable having a normal distribution with parameters μ and σ^2. To generate these realizations, a method from the text <u>Computer Simulation Techniques</u> (19) was used. Mathematically

$$\dot{x} = \mu + \sigma \cdot \left(\sum_{i=1}^{12} rn_i - 6 \right) \qquad (3\text{-}1)$$

where

rn = realization of a random variable uniformly distributed over [0,1].*

Having assigned a desired speed to that vehicle, an interarrival time for the next vehicle is computed. It was assumed that car arrivals follow a Poisson process,** so that the interarrival time is an exponential variable, with density function

$$f(x) = \frac{1}{b} \cdot e^{-x/b} \quad ; \quad x \geqq 0 \qquad (3\text{-}2)$$

$$= 0 \quad ; \quad x < 0$$

where

b = mean time between arrivals (seconds)

---

*Random numbers were generated via the multiplicative congruential method, as outlined in Appendix B.

**This approach is extensively discussed in reference 2.

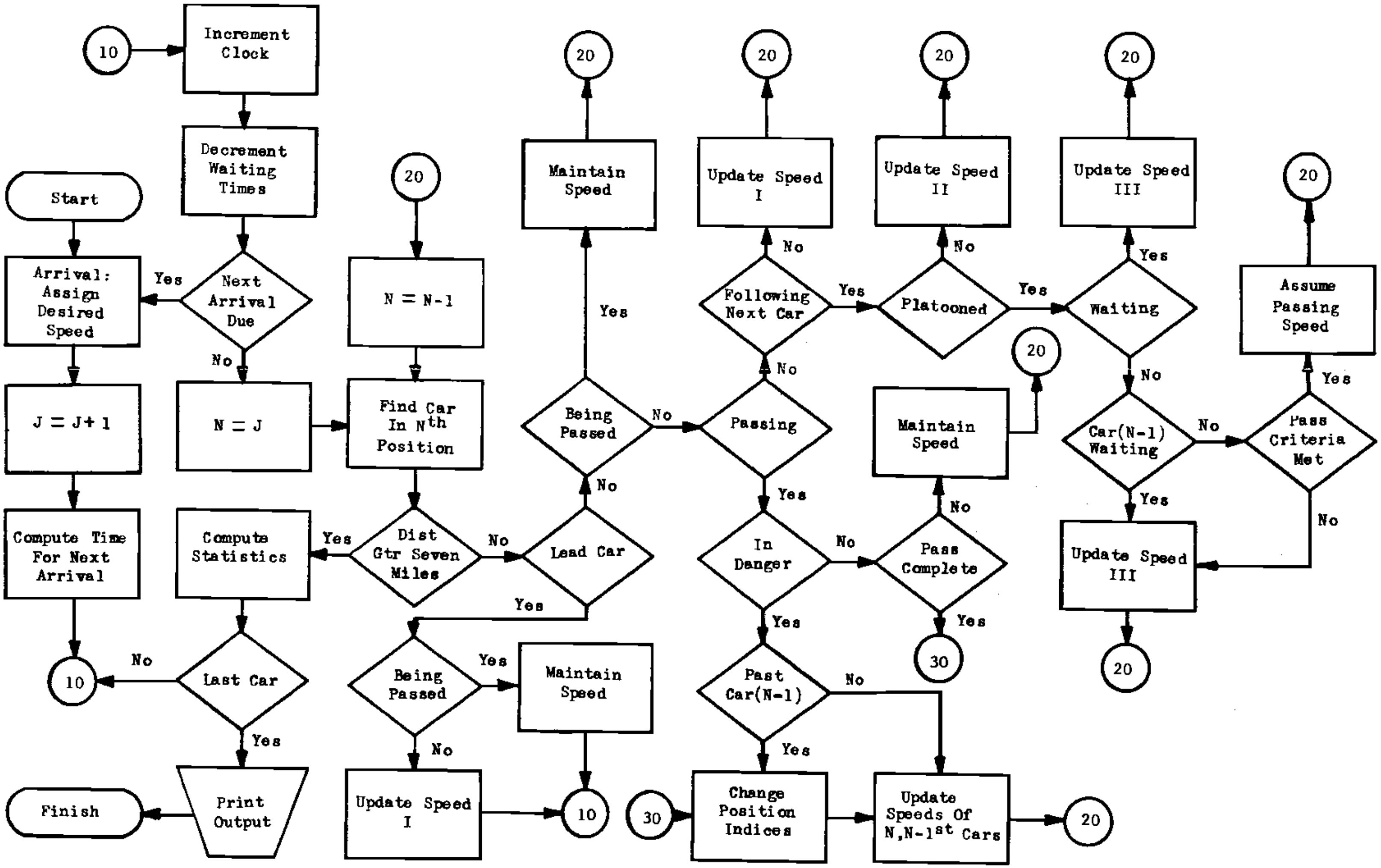

Figure 3. Flow Diagram for Simulation Model

The interarrival time would then be given by

$$t = -\ b \cdot \ln(rn) \tag{3-3}$$

However, a minimum headway must be specified if cars are to follow other cars logically.* This minimum headway was chosen to be one-half second. The modified interarrival time would have density function

$$\begin{aligned} f(x) &= \frac{1}{b} \cdot e^{-(x-\frac{1}{2})/b} \quad ; \quad x \geqq \tfrac{1}{2} \\ &= 0 \quad ; \quad \text{otherwise} \end{aligned} \tag{3-4}$$

The modified interarrival time, t', would then be given by

$$\begin{aligned} t' &= t + 0.5 \\ &= 0.5 - b \cdot \ln(rn) \end{aligned} \tag{3-5}$$

The algorithm then increments the clock, [10], and decrements the waiting time for each vehicle by one-half second. Next, it is determined if an arrival is due. If an arrival is due, then the previous procedure is executed. If, however, no arrival is due, the algorithm updates the speeds of all vehicles currently in the system according to method outlined in the remainder of this chapter.

The first step of the method is to set the variable "n" equal to the number of arrivals to date, "j". Then, the algorithm finds which car is actually in the n^{th} position. If that car has traveled seven

---

*The shifted exponential distribution is relevant for the case in which cars cannot pass at will. For a further discussion, see reference 6, pp. 484-485.

miles, then it is removed from the system, and its exit headway and average speed are determined. If this is the last car to be examined, then the program prints out all statistics, after which the program halts. However, if the car being examined is not the last car to be examined, then the algorithm returns to [10].

If the car being examined has traveled less than seven miles, then it is determined if that car is the lead car in the system. If it is the lead car, then its speed is updated according to whether or not it is being passed. If it is being passed, then it maintains its speed; if not, then it changes speed as follows

$$\dot{x}_n = \min(\dot{x}_n + 1, \dot{x}_{nd}) \text{ ft/sec} \tag{3-6}$$

where

$\dot{x}_{nd}$ = desired speed of the n^{th} car

The algorithm then returns to [10].

If the car being examined is not the lead car, then it is found if it is being passed. If it is being passed, then it maintains its speed and the algorithm returns to [20], so that the next car in the system can be examined. If, however, the car is not being passed, then the algorithm checks to see if the current car is passing another car. If it is passing, then it is determined if the passing car is dangerously close to the car ahead of the one being passed.* If it is in

---

*A car is considered to be dangerously close to the car ahead of the one being passed if the spacing between the passing car to the next car is less than $|\dot{x}_n|$ feet.

danger, then the passing car returns to the right lane. If the passing car was actually ahead of the car being passed, the position indices for the two cars are changed. Then the speeds of the passing car and the car being passed are updated according to the logic of Table 2, after which the algorithm returns to [20].

Table 2. Modification of Speeds for Closely Following Vehicles

Speed Relation	Spacing	New Speed in ft/sec
$\dot{x}_n \geqq \dot{x}_{n-1}$	$\leqq .7 \cdot \dot{x}_n$	$\dot{x}_n - C_3 \cdot \max(\dot{x}_n - \dot{x}_{n-1}, 4)$
$\dot{x}_n \geqq \dot{x}_{n-1}$	$> .7 \cdot \dot{x}_n$	$\dot{x}_n - C_4 \cdot (\dot{x}_n - \dot{x}_{n-1})$
$\dot{x}_n < \dot{x}_{n-1}$	--	$\min(\dot{x}_n + 1$, desired speed)

Note: C_3, C_4 sensitivity coefficients

If the passing car is not in danger, then the algorithm checks to see if the passing car is sufficiently ahead of the car being passed so that the passing car may safely return to the right lane.* If the pass is complete, then the algorithm changes the position indices and

*A passing car is sufficiently ahead of the one being passed if the passing car is $|\dot{x}_n|$ feet ahead of the car being passed.

speeds of the passed and passing cars [30], according to Table 2. If, however, the passing car cannot safely return to the right lane, then it maintains its speed, and the algorithm returns to [20].

If the car being examined is not passing, the algorithm checks to see if that car is distant enough from the next car so that it can act independently of it.* If this is the case, then a new speed is assigned to the current car according to Eq. 3-6, and the algorithm would then return to [20]. However, if the car may not act independently, then the algorithm checks to see if that car is close enough to the next car so that it may be considered to be platooned with it.** If the car cannot act independently of the next car, but is not platooned with it, then the current car obeys the car following law proposed by Edie (4)

$$\dot{x}_n = \dot{x}_n + \frac{C_2 \cdot \dot{x}_n \cdot (\dot{x}_{n-1} - \dot{x}_n)}{(x_{n-1} - x_n)^2} \tag{3-7}$$

where

C_2 = sensitivity coefficient

If the car is platooned, however, then it is determined if it is waiting to pass. This situation corresponds to the "refractory period" experienced between successive decisions to pass based on environmental criteria, or to the case in which the car in the opposing lane has

---

*A car may act independently of the next car if its intercar spacing exceeds $|3 \cdot \dot{x}_n|$ feet.

**A car is considered to be platooned with the next car if its intercar spacing is less than $|20 + .9 \cdot \dot{x}_n|$ feet.

not yet passed by the car being examined. If the car is waiting, then its speed is updated according to Table 2, and the algorithm returns to [20]. If the current car is not waiting, then the algorithm examines the $n-1^{st}$ car to see if it is waiting to pass. If this is the case, then the car now being examined (n^{th} car) must also wait, since precedence in passing is given to the car directly behind the lead car in any platoon. The new speed of the n^{th} car would then be computed according to Table 2, and the algorithm would return to [20].

If, however, the $n-1^{st}$ car is not waiting to pass, then the n^{th} car may consider a pass. The four requirements which must be satisfied are these:

1. The current car must have a desired speed in excess of five percent of the current speed of the car to be passed.

2. The car must not be in a no-passing zone.

3. The gap in the opposing lane must be sufficient to permit the pass to be safely executed.

4. The expected spacing, upon completion of the passing maneuver, between the current car and the car ahead of the one to be passed, must be sufficiently large to allow the current car to pass safely.

The first condition is self-explanatory. The second condition is tested by comparing a random number with the percentage of no-passing road length.* The third condition was examined by making use, in part, of the work of Prisk (20) mentioned earlier. Specifically, the gap perceived as being necessary to allow a pass was composed of three compo-

---

*In this study, it was assumed that there were no no-passing zones.

nents: the distance actually spent in the left lane, D1, the desired gap between the passing car and the opposing car upon completion of the pass, D2, and the distance the opposing car would have traveled while the pass was taking place, D3. The first component, distance traveled while in the left lane, was assumed to be

$$D1 = \frac{\dot{x}_{np} \cdot (x_{n-1} - x_n + |\dot{x}_{np}|)}{(\dot{x}_{np} - \dot{x}_{n-1})} \quad \text{(feet)} \tag{3-8}$$

where

$$\dot{x}_{np} = \text{average passing speed}$$
$$= K1 \cdot \dot{x}_n$$

Values computed with this equation closely approximate those observed by Prisk.

The desired gap between the opposing car and the passing car upon completion of the pass, D2, as given by Prisk, and the "refractory period" he observed, T1, are given in Table 3, along with the values of K1.

The expression for D3, as given by Prisk, is

$$D3 = 2 \cdot D2/3 \quad \text{(feet)} \tag{3-9}$$

The safe passing gap, then, is

$$S = D1 + D2 + D3 \quad \text{(feet)} \tag{3-10}$$

The gap in the opposing lane was generated as a realization of a random variable from an exponential distribution, whose mean value was chosen to be a multiple of the mean arrival headway (feet).

Table 3. Components of Passing Distance Estimate

Speed Group (mph)	D2 (feet)	T1 (sec)	K1
0 - 19	65	3.0	1.20
20 - 29	100	3.3	1.18
30 - 39	140	3.6	1.16
40 - 49	180	3.9	1.14
50 - 59	240	4.1	1.12
60 - 69	280	4.3	1.10
70 - --	300	4.4	1.08

$$G = rn \cdot b \cdot \dot{x}_{avg} \cdot \mu \qquad (3\text{-}11)$$

where

$\dot{x}_{avg}$ = mean desired speed in opposing lane

μ = measure of relative density of opposing traffic to main-stream traffic

To satisfy the third condition, the ratio G/S must exceed unity.

The fourth condition is that of a safe expected final spacing between the passing car and the car ahead of the one to be passed. This final critical spacing was chosen to be $|2 \cdot \dot{x}_{np}|$ feet. The expected spacing is a function of relative speeds and initial relative distances, namely

$$ES = x_{n-2} - x_n - D1 \cdot \left(1 - \frac{\dot{x}_{n-2}}{\dot{x}_n}\right) \quad \text{(feet)} \qquad (3\text{-}12)$$

If the preceding four conditions were met, the car wishing to pass immediately assumed its average passing speed, and the algorithm then returned to [20]. If, however, these conditions were not met, then the car wishing to pass must be assigned a waiting time. The waiting time assigned was either the value T1 (refractory time), or the time required for the opposing vehicle to pass by, whichever was larger. A new speed was then assigned to the car being examined according to Table 2. The algorithm then returned to [20].

The preceding largely completes the explanation of the flow diagram. Bookkeeping and control elements were not included in this discussion but are straightforward in nature.

Some of the specific relationships and quantities of interest to be studied in this research are the following:

1. The relationship of flow rate and density at highway speeds.

2. The relationship of average speed to desired speed and traffic volume.

3. The effect of desired speed and traffic volume on the formation of platoons.

4. The effect of desired speed and traffic volume on the amount of passing.

5. The relationship of the exit headway distribution to the arrival headway distribution.

Experimental Design

To answer these questions, a factorial design was set up in which a wide range of desired speeds was associated with varying arrival mean headways and opposing mean headways. In the following figure, desired speed is represented by "A", mean arrival headway by "B", and the multiple (1,2) of the arrival which was used to obtain the mean opposing headway by "C".

		A				
B	C	20	30	40	50	60
6.5	1					
	2					
12.5	1					
	2					
18.5	1					
	2					

Figure 4. Experimental Design

Some of the measured variables are:

1. Average platoon size
2. Mean and variance of exit headways
3. Average number of passes per vehicle
4. Stream average speed
5. Desired speed versus average speed for each car
6. Exit headway for each car.

Field Study

To validate the model, a field study was made on a two mile stretch of road on Highway 78, in Gwinnett County, Georgia, on August 2, 1968, between the hours of 4:00 p.m. and 5:15 p.m. Four experimenters took part. In each direction, an experimenter attempted to drive at one of three desired speeds (65, 60, or 55 mph). After each run, the average resultant speed was recorded. Three runs were made for each desired speed-direction category. A 1964 model six cylinder Chevrolet was used to make the runs. The lengths of no-passing zones were recorded. Also, the volume in each lane and the mean observed speed for each lane were found with the aid of an Esterline-Angus event recorder and an Enoscope. The simulations which were subsequently performed for validation incorporated as parameters the traffic volume and no-passing zone values observed in the field. Mean mainstream desired speed for each simulation was set equal to that speed which would yield a stream mean speed equal to that observed in the field, for the relevant direction of flow. The results of the field study will be discussed in the following chapter.

CHAPTER IV

DISCUSSION OF RESULTS

The experimental design used to study effects on average speeds, platooning, passing, and flow rates consisted of a factorial arrangement of three independent variables: desired speed, mean mainstream headway, and mean opposing headway. Five desired speed levels, three mainstream mean headway levels, and two opposing mean headways for each value of mean mainstream headway were chosen and considered as fixed levels.

Average Speed

The average speeds attained, for each combination of headways and desired speeds, are shown in Figure 5. The three factor analysis of variance test showed that the only significant effect (five percent) was desired speed. However, when an analysis was made by breaking out each level of desired speed, it was found that mainstream headway had a significant (10 percent) effect for each level of desired speed, but that the opposing headway had no significant effect. The implication of this result is that attained speed, when passing is permitted, is more dependent upon congestion within the mainstream than congestion in the opposing stream.

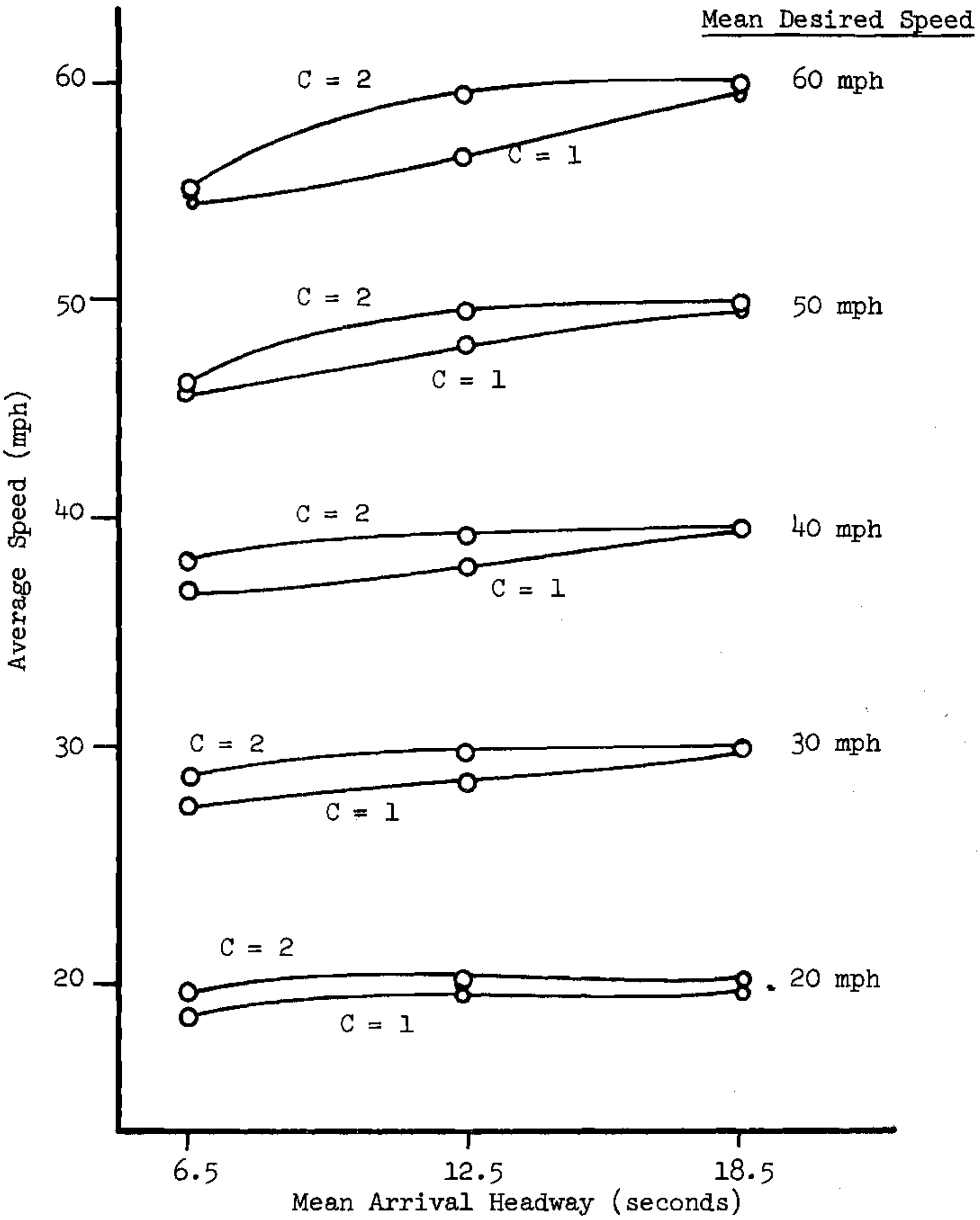

Figure 5. Average Speed for Desired Speed Category (Mean Opposing Headway = C Times Mean Arrival Headway)

Platooning

The average platoon size, for all combinations of speeds, mainstream headways, and opposing headways, is shown in Figures 6, 7, 8, and 9. The three factor ANOVA showed that mainstream and opposing headways, and their interaction, were significant (one percent), but that desired speed had no significant effect. The only case in which speed appears to have an important effect is where desired speed is at a low level in combination with low mainstream and opposing headways.

The above results can be explained qualitatively. Cars entering the system at low headway levels are initially more apt to be platooned. Since the mainstream is then congested, there is less likelihood of being able to pass than would be the case for large mainstream headways. Since mean opposing headways were taken to be multiples of mean mainstream headways, an interaction of mainstream and opposing headways would be expected. Had the mean values of opposing headways been chosen independently, then the second order interaction would probably not have been significant. The fact that headways had greater effects at lower levels of desired speed is not so easily explainable. One hypothesis is that passing is much more sensitive to headways when at low levels of desired speed than at higher levels of desired speed. That this was, in fact, the case is shown in the next section.

Passing

The average number of passes per vehicle, for each combination of headways and desired speeds, is shown in Figures 10, 11, 12, and 13. It was found that speed and opposing headways have significant (five

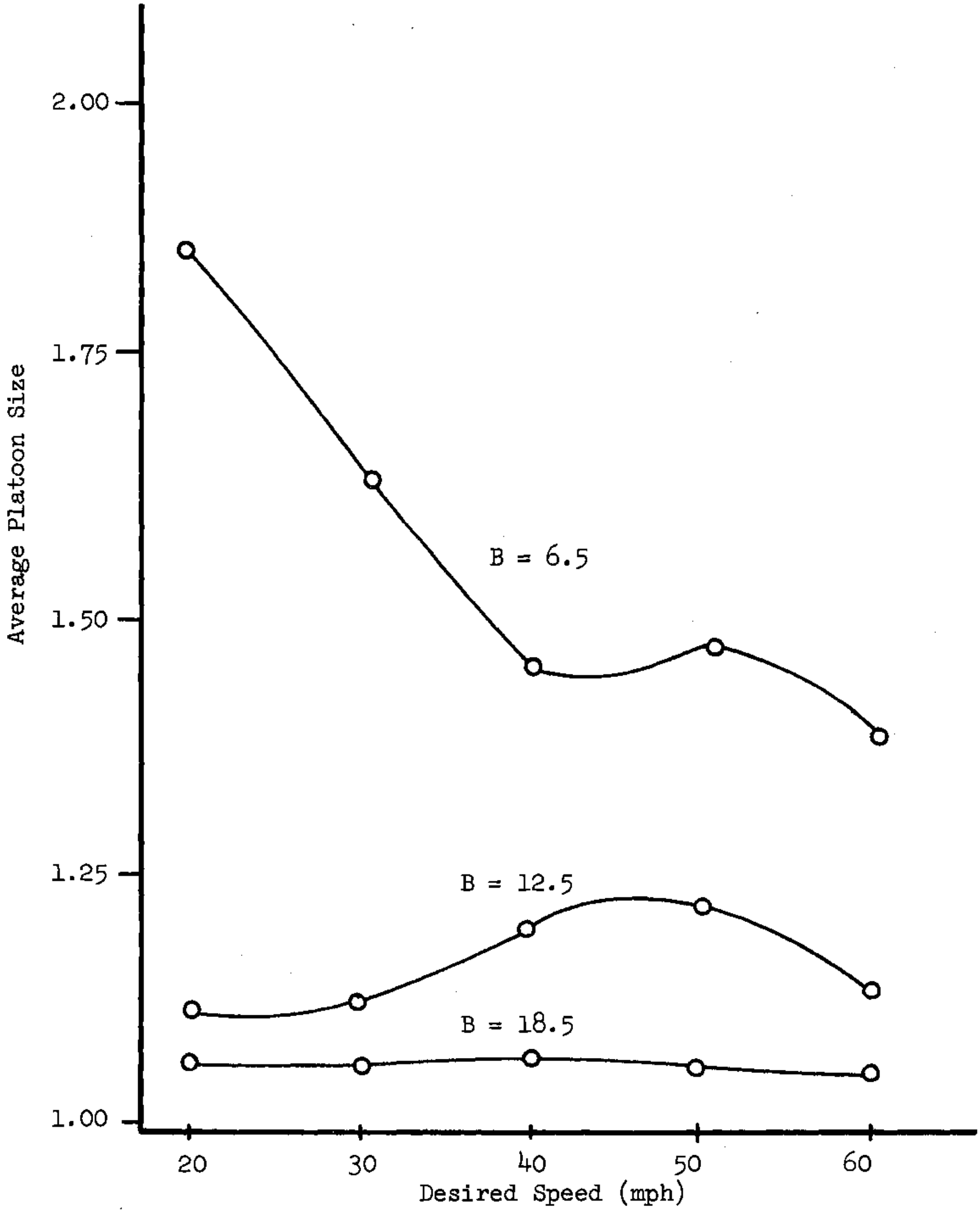

Figure 6. Average Platoon Size When Mean Opposing Headway = Mean Arrival Headway (B (seconds))

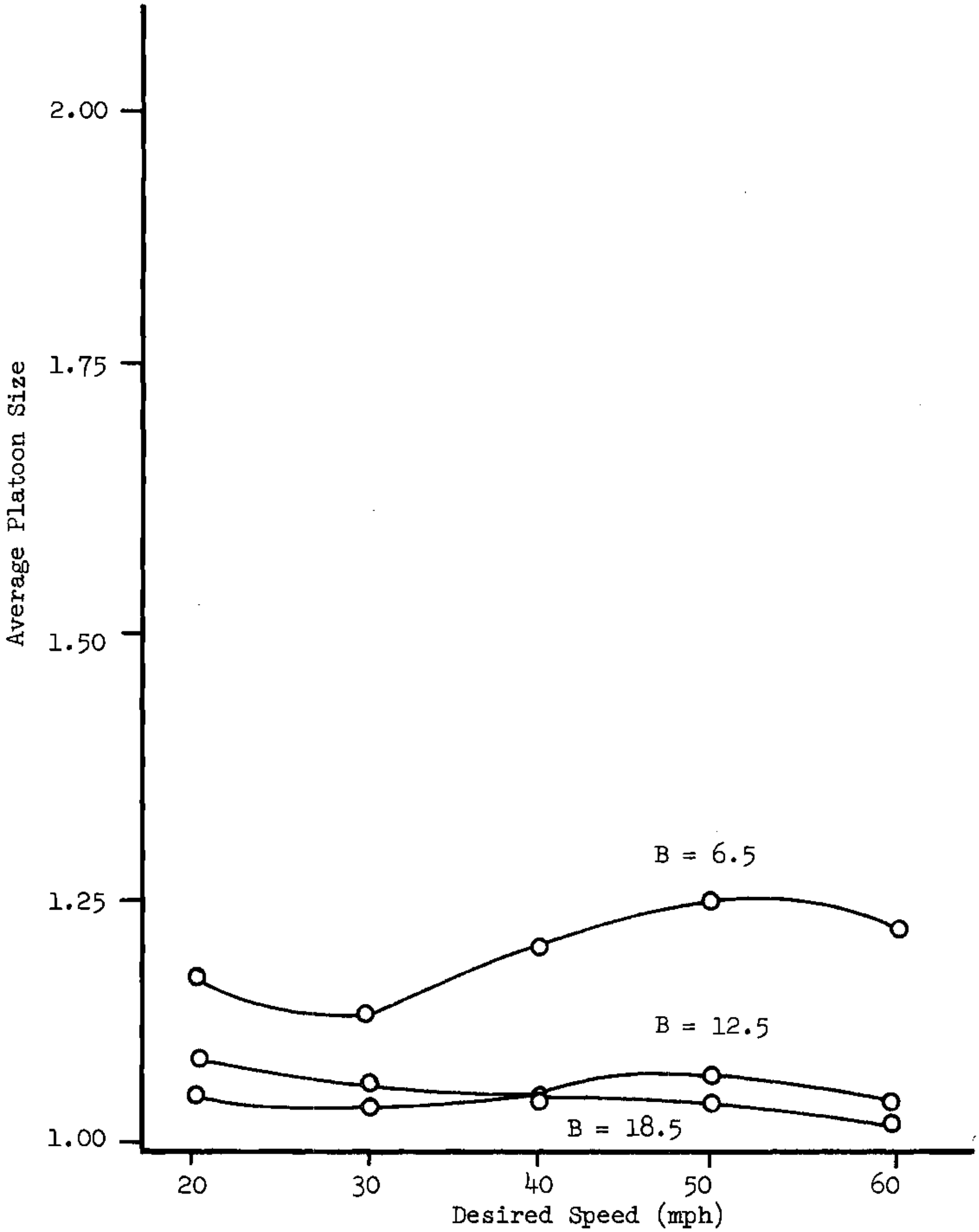

Figure 7. Average Platoon Size When Mean Opposing Headway = Twice Mean Arrival Headway (B (seconds))

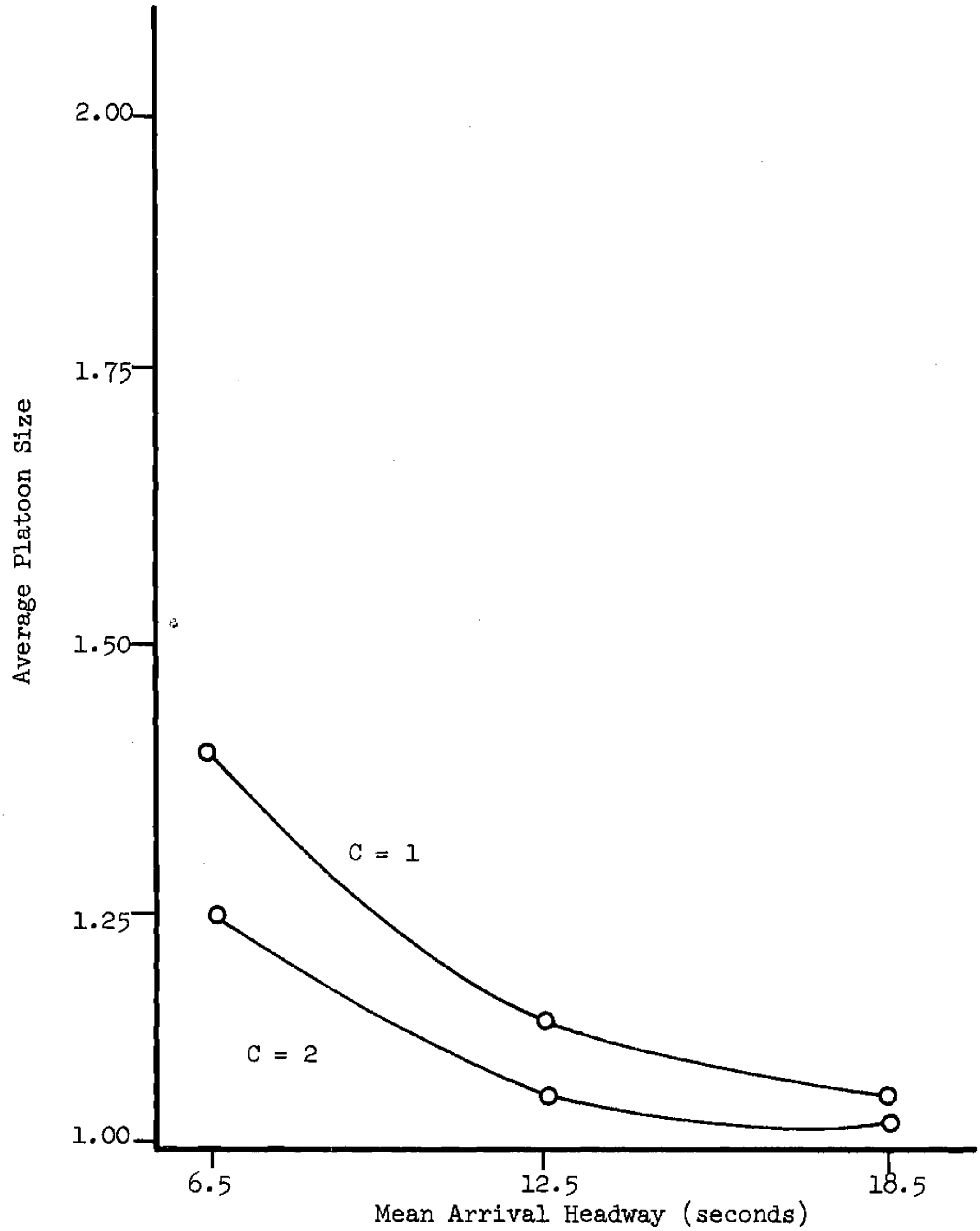

Figure 8. Average Platoon Size When Mean Desired Speed = 60 mpn (Mean Opposing Headway = C Times Mean Arrival Headway)

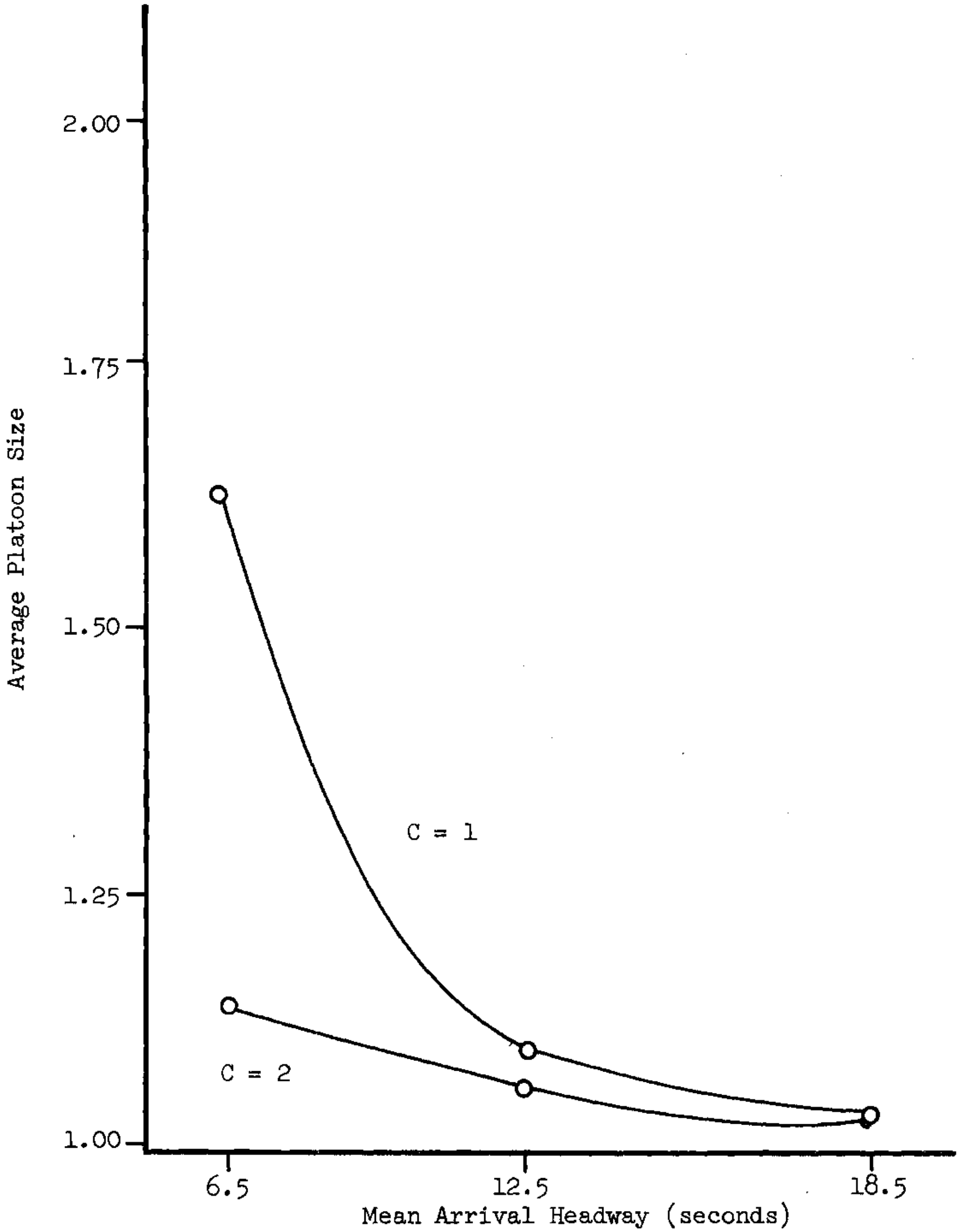

Figure 9. Average Platoon Size When Mean Desired Speed = 30 mph (Mean Opposing Headway = C Times Mean Arrival Headway)

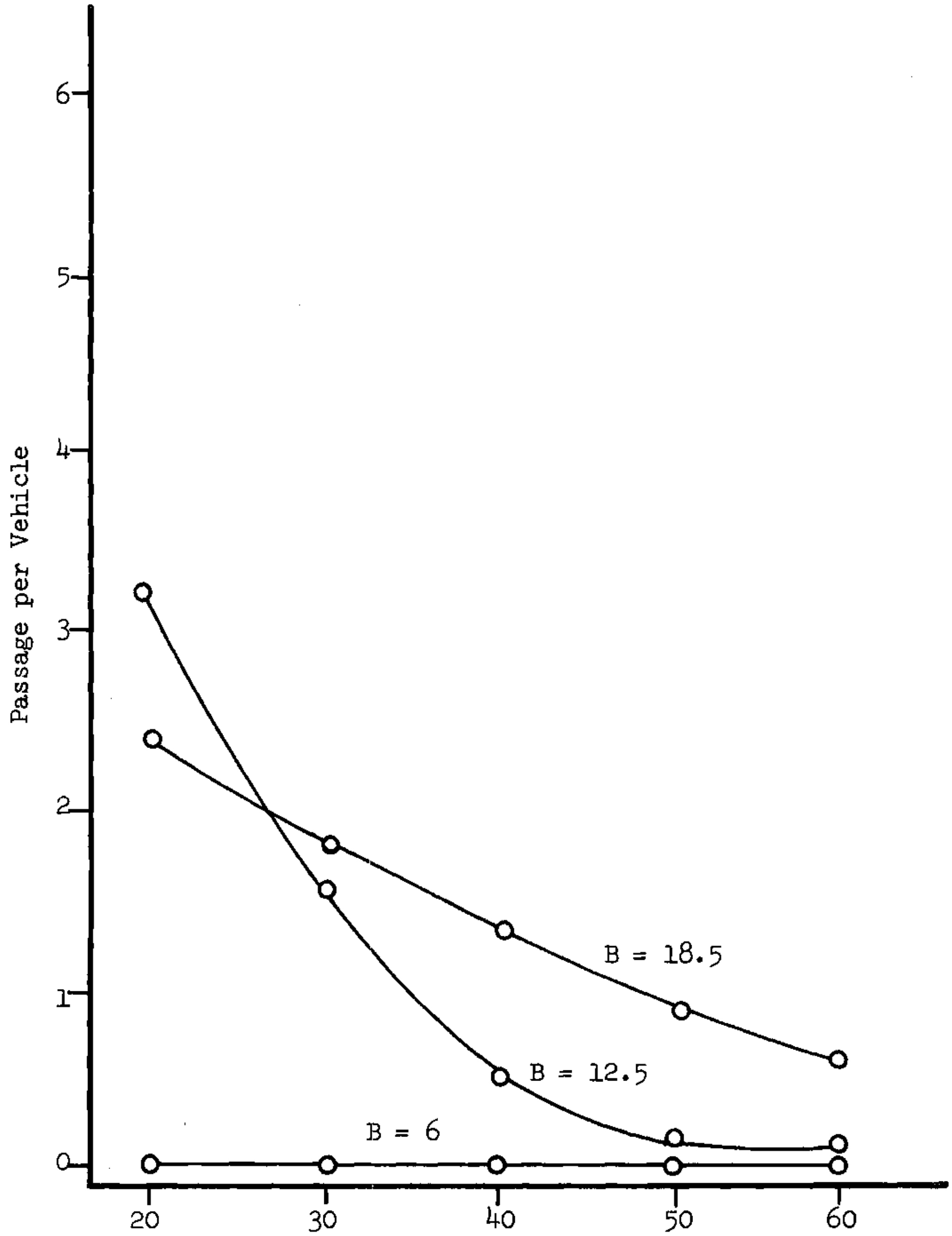

Figure 10. Average Number of Passes per Vehicle When Mean Opposing Headway = Mean Arrival Headway (B (seconds))

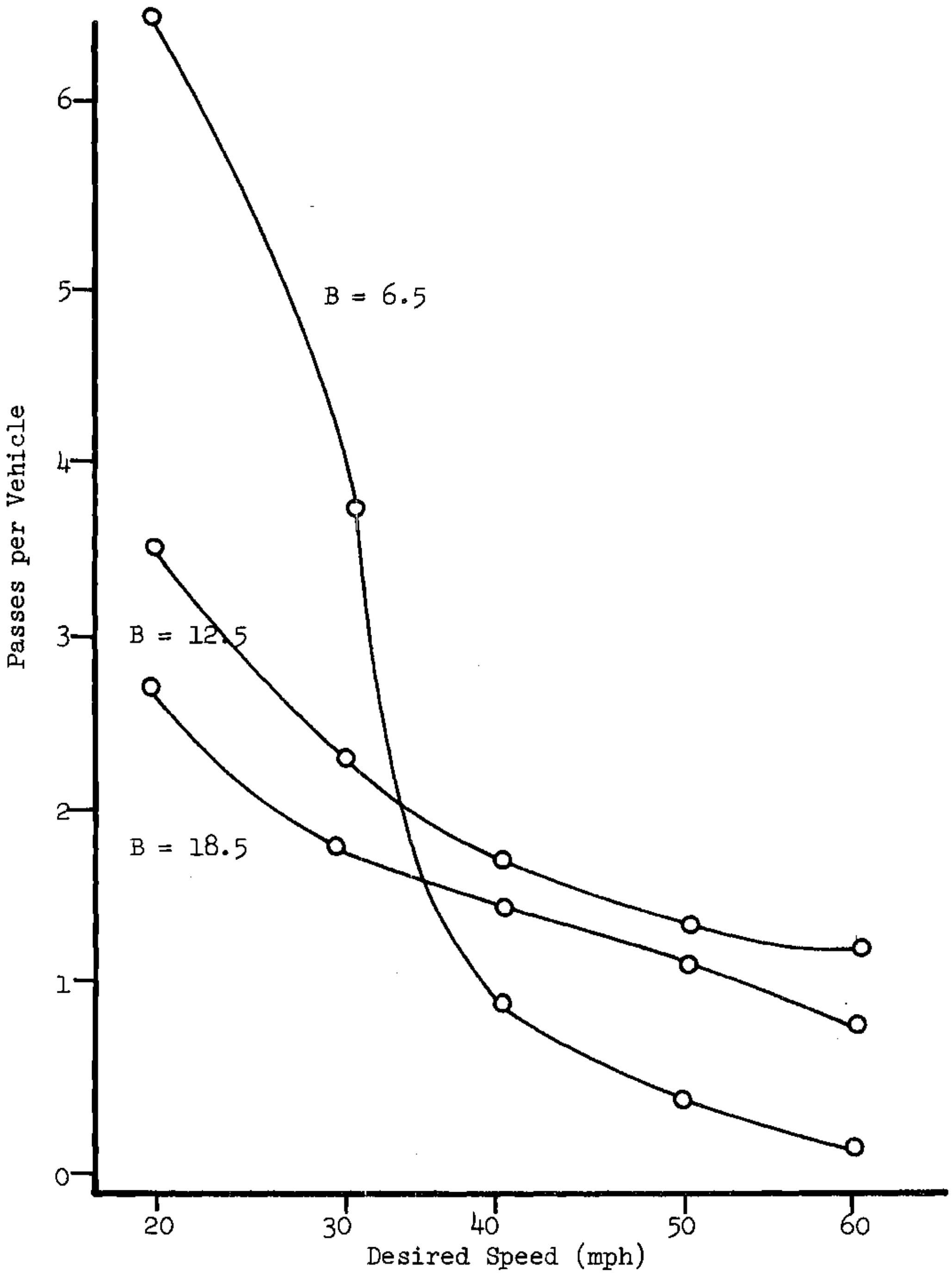

Figure 11. Average Number of Passes per Vehicle When Mean Opposing Headway = Twice Mean Arrival Headway (B (seconds))

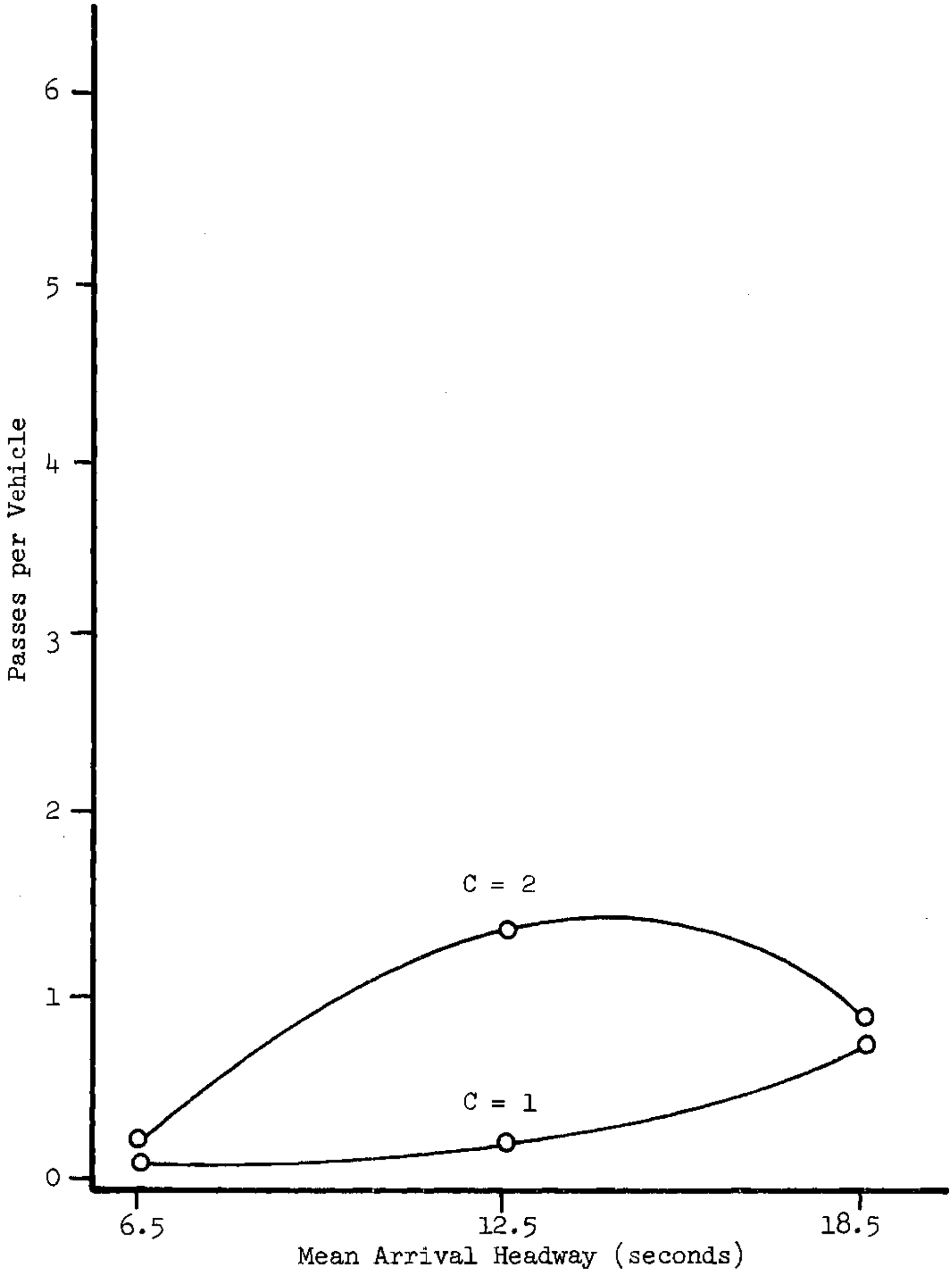

Figure 12. Average Number of Passes per Vehicle for Mean Desired Speed of 60 mph. (Mean Opposing Headway = C Times Mean Arrival Headway, B (seconds))

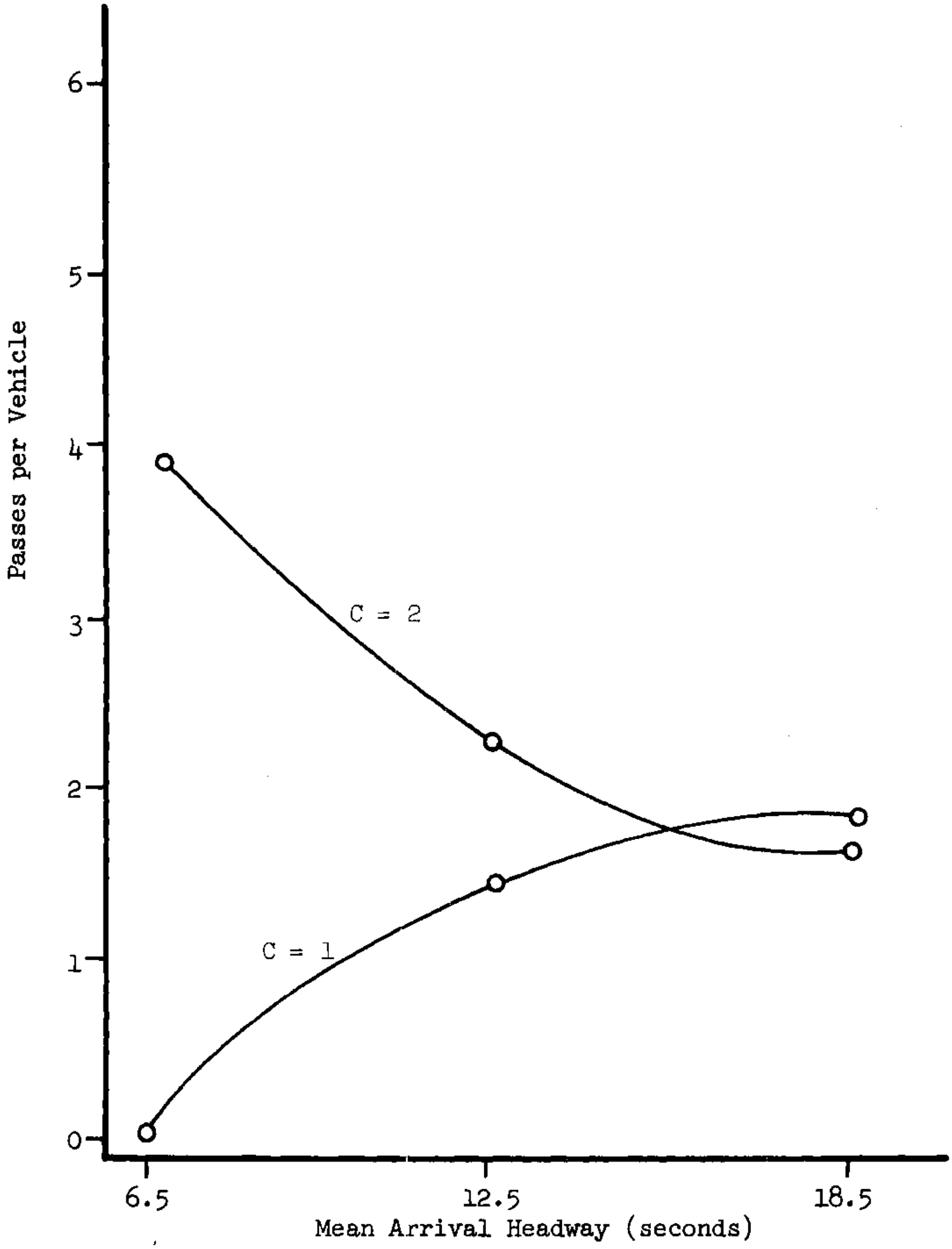

Figure 13. Average Number of Passes per Vehicle for Mean Desired Speed of 30 mph. (Mean Opposing Headway = C Times Mean Arrival Headway, B (seconds))

percent) main effects, while mainstream headway had no significant effect. A second order interaction of mainstream and opposing headways was also found to be significant (10 percent).

Considering the effects of speed and opposing headways, it is seen that, as the level of desired speed is decreased, the amount of passing is increased. It may be argued that, at high levels of desired speeds, cars follow other cars at larger distances and that they seek higher final intercar spacings after having passed other vehicles. For a given relative speed, then, it would take more time to overtake another car and return to the right lane when speed is at a high level than when speed is at a lower level. It would seem, upon examination of Figures 10 and 11, that the effect of speed is approximately quadratic in this regard. Examination of Figures 12 and 13 shows that the effect of opposing headways is markedly different for low levels of speed than for high levels of speed. For low speed levels, there is a wide divergence between the amount of passing for small opposing headways and the amount of passing for higher opposing headways, while at higher speeds, the values tend to converge. This fact strengthens the argument that the effect of opposing headway is more significant for lower levels of speed than for higher levels of speed.

Flow Rate

The best fit curves for flow rate out of the system are shown in Figures 14 and 15. Figure 14 shows flow rate when mean opposing headways equal mean mainstream headways, while Figure 15 shows flow rate when mean opposing headway equals twice the mean arrival headway.

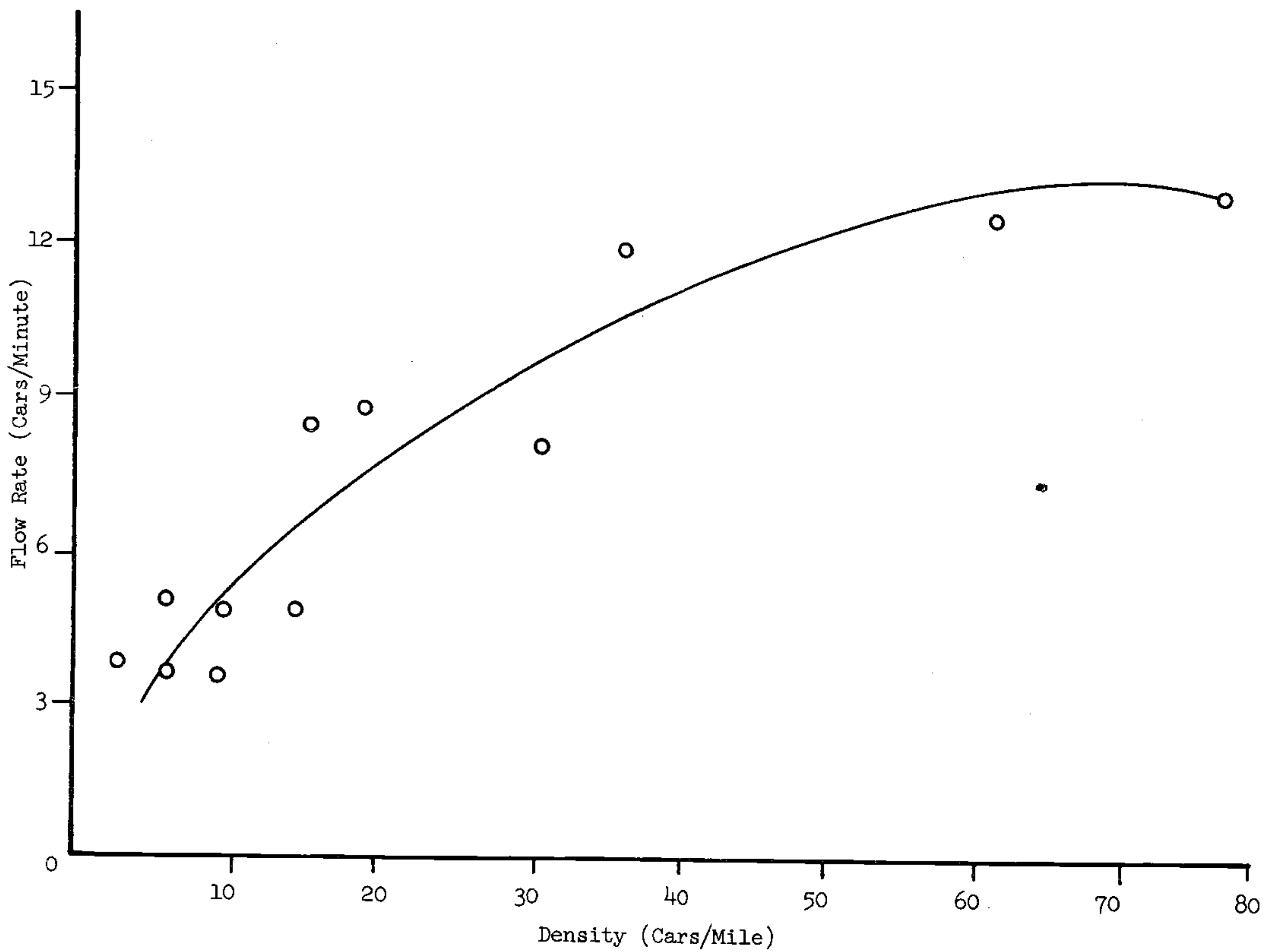

Figure 14. Flow Rate When Mean Opposing Headway = Mean Arrival Headway

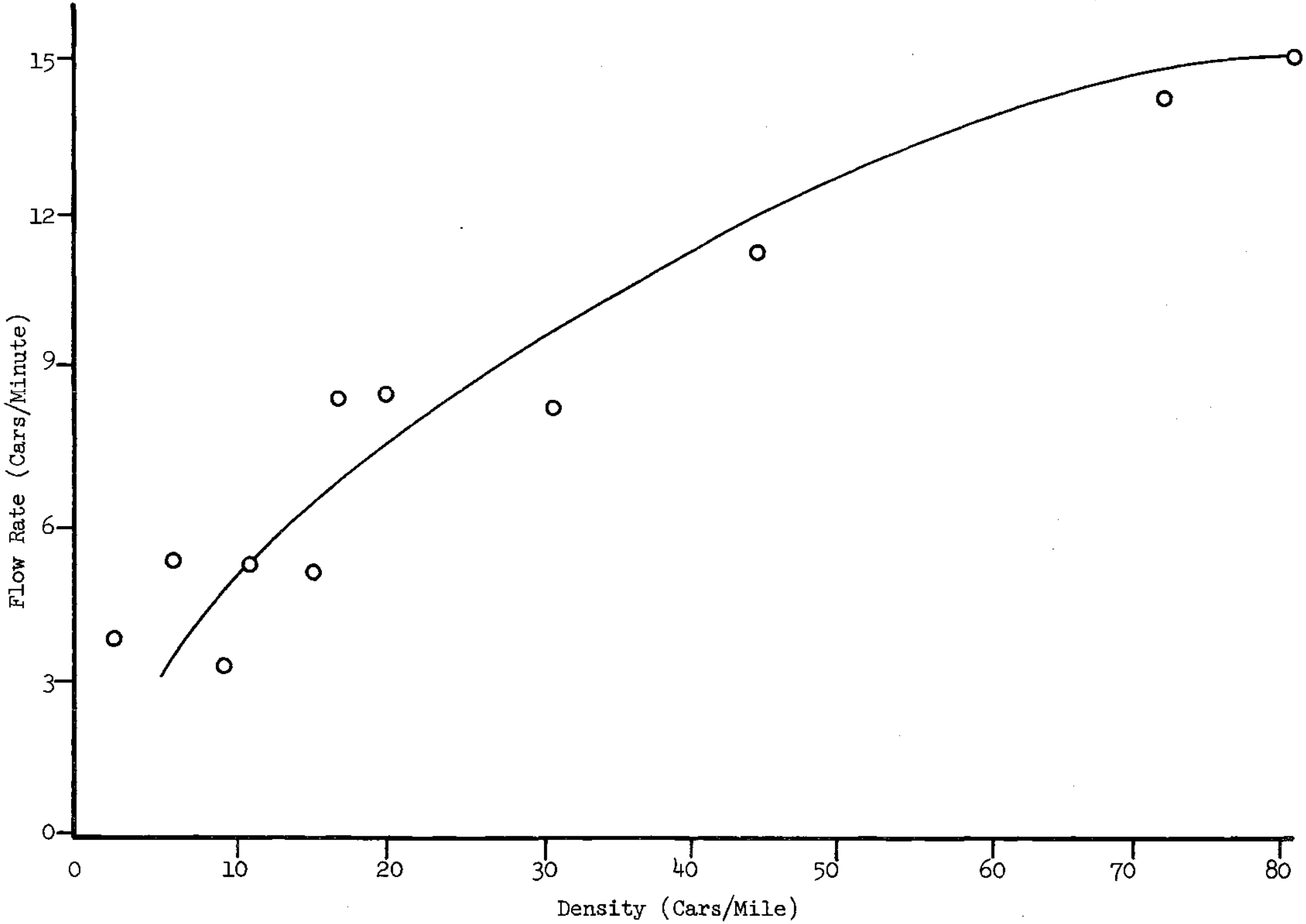

Figure 15. Flow Rate When Mean Opposing Headway = Twice Mean Arrival Headway

There is no apparent difference in the magnitudes or shapes of the two curves. This leads to a hypothesis that opposing headways have little effect in determining the flow rate, for low and intermediate densities. The data also revealed that mean output headway was, for each simulation, very nearly equal to the mean arrival headway, while for a given mean arrival headway, speed had little effect in determining the mean output headway or flow rate. This result implies that the flow rate out of the system is approximately equal to the flow rate into the system. Considering the relatively large input mean headways considered in this study, this result is not surprising.

The obtained curves agree, generally, with the empirical observations for light and intermediate flows, although the empirical observations made by the Road Research Laboratories yielded slightly larger levels of flow for the low volume case. This agreement is felt to be in partial validation of the simulation model. It must be kept in mind, however, that the empirical observations were made under a no-passing environment.

In Figures 16, 17, 18, and 19 are plotted the distributions of exit headways observed for simulations involving mean desired speeds of 30 and 60 miles per hour, in combination with mean arrival headways of 6.5 and 18.5 seconds. An examination of these curves shows that, as stated earlier, speed and opposing headways have little effect in determining the exit headway (flow). The differences between the shapes of the arrival and exit headway distributions are more dramatic for the case of small arrival headways than for large arrival headways.

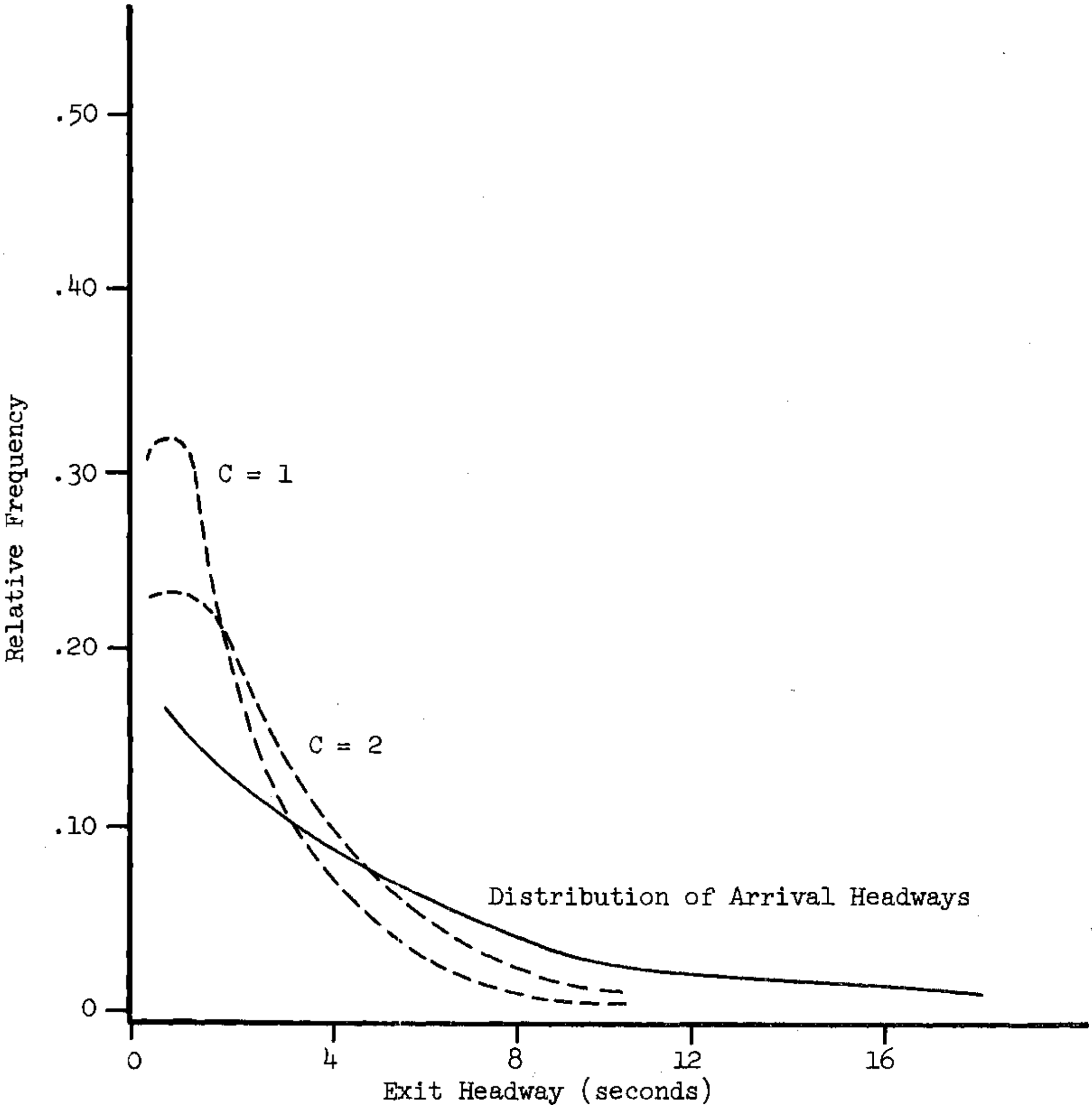

Figure 16. Exit Headway Distributions When Mean Arrival Headway = 6.5 Seconds and Mean Desired Speed = 30 mph. (Mean Opposing Headway = C Times Mean Arrival Headway)

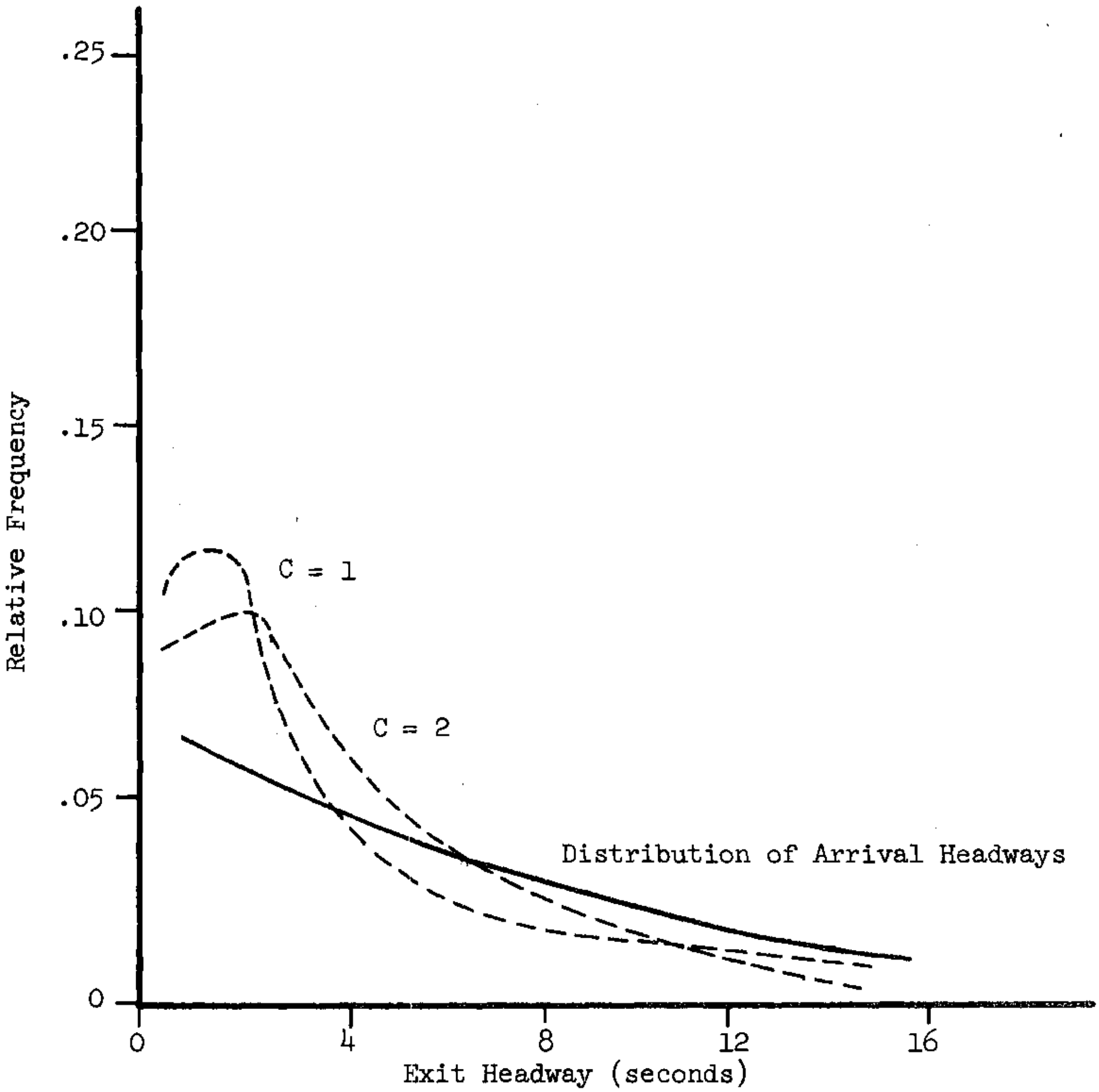

Figure 17. Exit Headway Distributions When Mean Arrival Headway = 18.5 Seconds and Mean Desired Speed = 30 mph. (Mean Opposing Headway = C Times Mean Arrival Headway)

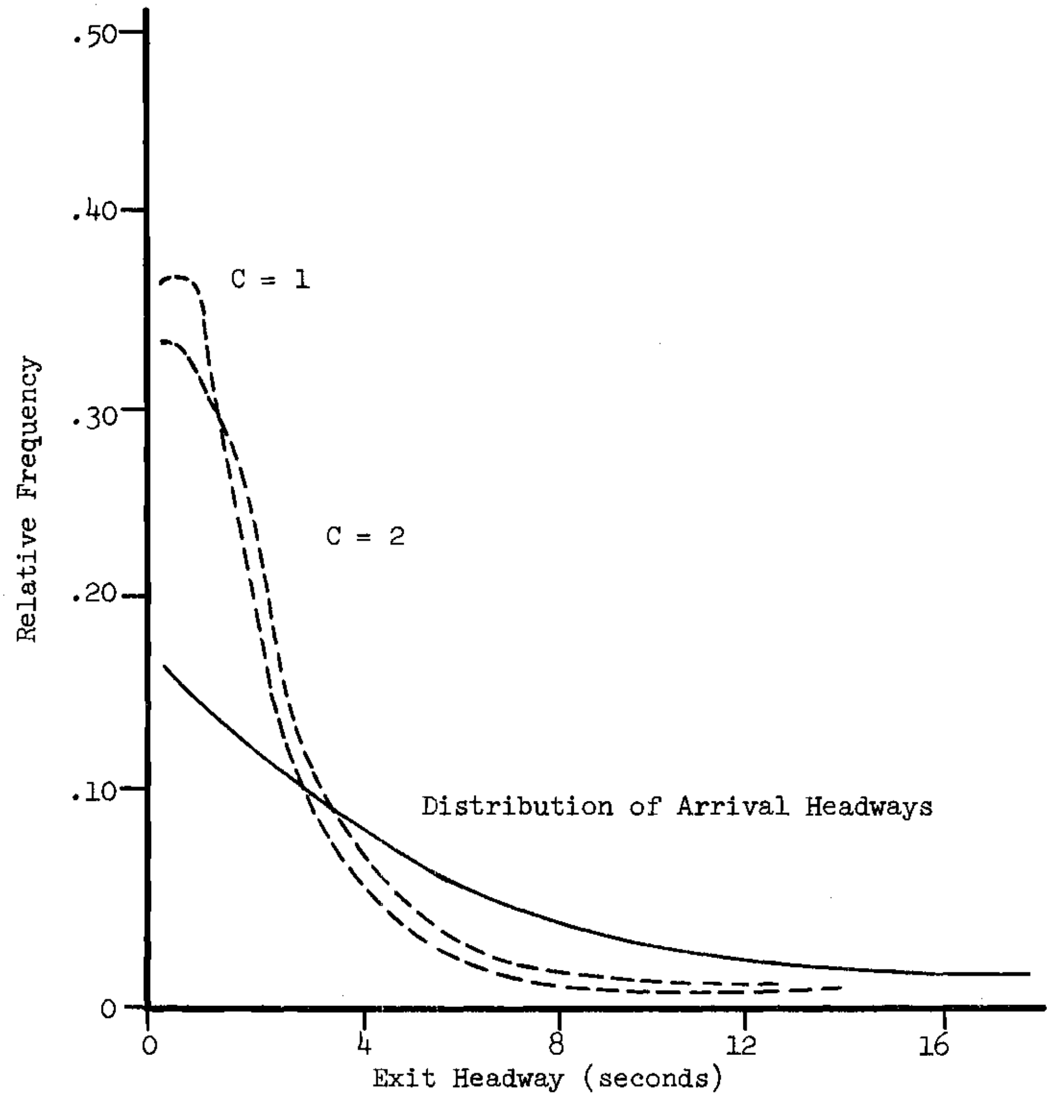

Figure 18. Exit Headway Distributions When Mean Arrival Headway = 6.5 Seconds and Mean Desired Speed = 60 mph. (Mean Opposing Headway = C Times Mean Arrival Headway)

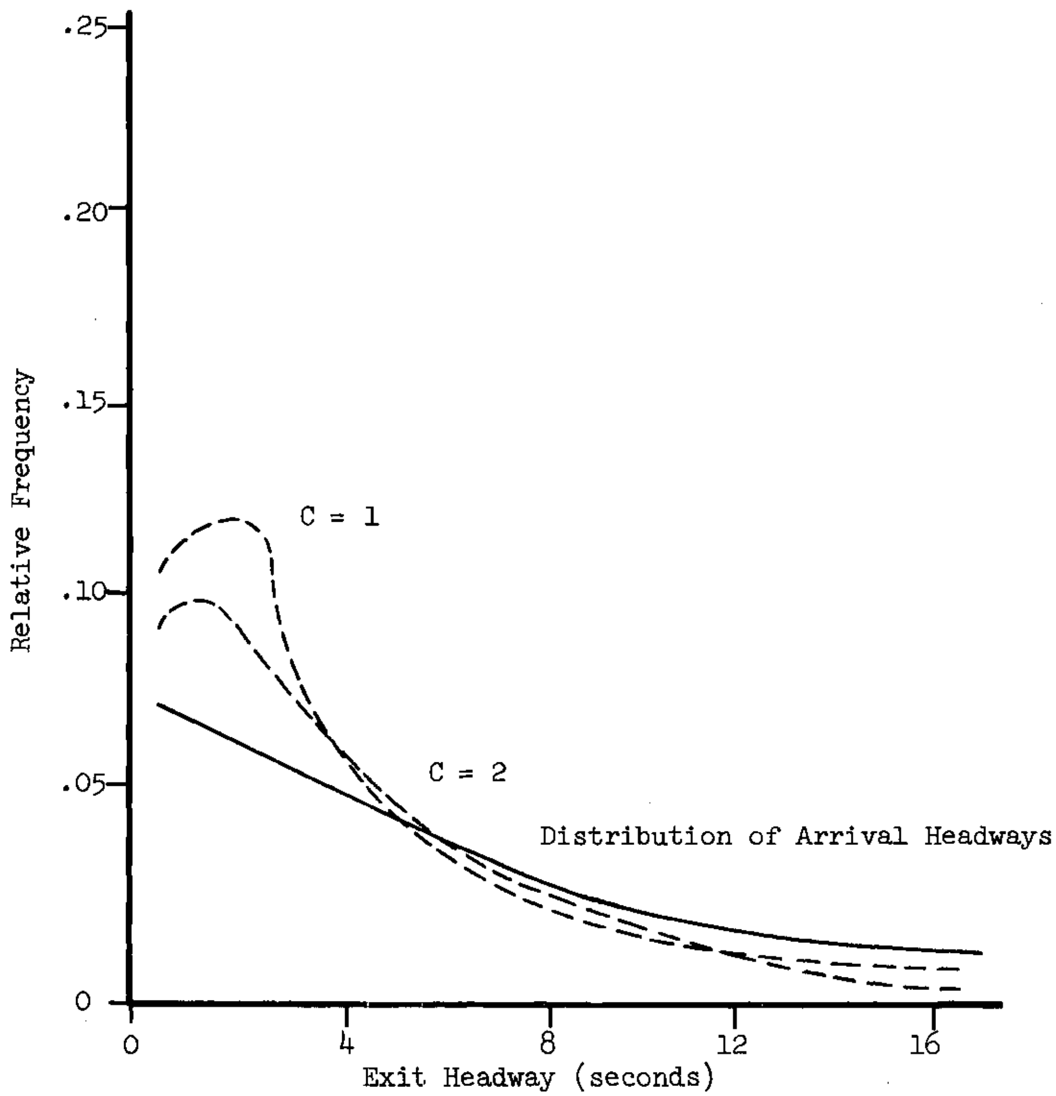

Figure 19. Exit Headway Distributions When Mean Arrival Headway = 18.5 Seconds and Mean Desired Speed = 60 mph. (Mean Opposing Headway = C Times Mean Arrival Headway)

The decreased possibility of passing when mainstream headways are small, causing cars to be more permanently platooned, is one reason why there is such a large concentration of small exit headways for the case of small arrival headways. Additionally, cars are initially at smaller spacings for the high volume case.

The shape of the exit headway distributions compares favorably with observed distributions and with certain distributions proposed by traffic flow theorists. For a comparison, see Buckley (2).

Field Study Validation

The results of the field study are summarized in Table 4. The theoretical values were derived by performing three separate simulations for each direction of travel, with each simulation run being based on a different random number seed. The theoretical average attained speed, for a given desired speed, was obtained by sampling each simulation result. The attained speed, which was paired with each pertinent desired speed, was used to obtain the theoretical attained speed values shown for each direction of travel.

The average error between the field study data and theoretical results is 1.5 miles per hour overall. Through further field study, the accuracy of the model could be more closely determined.

Table 4. Results of Field Study

Direction of Travel	Desired Speed	Average Speed (Field Trials)	Average Speed (Simulation)
East	65	52.3	55.3
East	60	53.1	53.4
East	55	51.4	52.9
West	65	62.0	61.4
West	60	54.3	57.5
West	55	54.6	54.9

Table 5. Values of Field Study Parameters

	Eastbound	Westbound
Stream Mean Speed	50.6	58.3
No-passing Zones	35 %	25 %
Mean Headway (secs)	9.5	16.5

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The discussion in Chapter IV and the conclusions drawn therefrom must be considered only within the context of the particular system which was defined in this research. Specifically, the discussion in this chapter is based on a system that was initially empty and for which statistics were computed for a relatively small number of vehicles (two hundred). In summary, the data reflect the assumptions and limitations mentioned previously, and the statistics probably reflect transient effects. With this statement as a preface, the following conclusions are made.

For all volume relationships, both average platoon size and amount of passing will be at their lower levels when stream mean speed is at a high level. Passing is decreased at high speed because drivers then seek higher intercar spacings. The effect of the opposing headway on the passing situation is much more evident for the low speed case than for the high speed case. Since relatively little time is required to pass at low speed, the primary determinant of passing is probably the amount of traffic in the opposing lane, for the low speed case. For the high speed case, the effect of opposing traffic on passing is slight.

It is obvious that attained speed is dependent on desired speed. It was found, however, that the only other significant effect on speed was volume of traffic in the mainstream. If this is the case, then it would seem that highways are inferior to expressways only in the volume of traffic that can be accommodated.

The maximum flow rate is achieved for intermediate densities. In general, increases in density and, hence, the flow rate, are achieved only through a decrease of speeds and mainstream headways. The speed limit could be made variable and set inversely to the volume rate of traffic arrivals to achieve a high flow rate.

While mean exit headways approximately equaled mean arrival headways, the shape of the headway distribution changed dramatically as the cars moved over the simulated road course. This difference was especially noticeable for heavy flows, reflecting the platooning that occurs under these conditions.

Recommendations

Further study of the topics pursued in this research should be made in order to eliminate some of the shortcomings of this study. In specific, the system should be initialized before statistics are gathered on subsequent vehicles. Also, it is advisable that other arrival headway distributions be considered for use as input to the model. One distribution that might be considered is the exit headway distribution as shown in any of Figures 16, 17, 18, or 19 in Chapter IV of this research report.

The simulation program used for the present research gives traces of the number of cars past each of eight equally spaced (200 feet) points, at equal (five second) intervals of time. By examining this set of traces, it is possible to determine the characteristics of disturbance propagation, such as speed of propagation and time required to damp out the disturbance. These characteristics could be studied under varying levels of speed, headways, and driver sensitivities. Although the study would be quite large, many of the questions examined by previous researchers could be answered within a system context.

Another area to be considered is the nature of an individual driver's behavior as he reacts under different sensitivities or speeds of reaction. Using the results of the study outlined in the previous paragraph, it would be possible to then discuss a "limiting variance" element which would be the maximum allowable variance element that could safely be allowed in highway traffic. By appropriate driving tests, a driver's variance, or sensitivity, could be measured and compared with the "limiting variance," to determine if it were safe for that driver to drive in highway conditions.

As a final topic, consider the possibility of a network traffic study. Using total flow through the network as a criterion, speed-volume relations could be established to maximize that criterion. Although much work has been accomplished in this area by operations research methods, a simulation study could add credence to the results obtained to date.

APPENDICES

APPENDIX A

COMPUTER PROGRAM AND TYPICAL OUTPUT

```
BEGIN
INTEGER B1,DENSITY,C,PAST,G,NEXT,I,F,S,Z,MU,DEV,UP,L,J,K,P,M,U,N,
        PASS,NUM,PLAT1,BI,TUNIT,RI ;
REAL    V,V28,N1,N2,N3,N4,C1,C2,C3,C4,C5,C6,OUTA,FACT,DENOM,NORM,TOTEL,
        TDLY,INT,R,CT,K1,T1,T2,D2,D3,D1,ACL,CHOICE,SAFEGAP,VAR,GAP,
        CLICK,CLOK1,CLOK2,CLOCK,RN,ATOTL,A100,EACH,PLAT,CLACK,MEAN;
REAL ARRAY TIME,AVG,ENTRY,THRU,DECISION,DANGER,DES,ACT,DIST,WAIT,
           TWAIT,OUTOF,MIL[0:201],PT[0:9,0:200],AX[0:9,0:600];
INTEGER ARRAY SPD[0:1000],FLIP,FLAP,CAR,UNIT[0:201],XT,PX[0:9];
STRING A(120);
LIST  LS(N1,N2,N3,N4),LIST1(N,CAR[N],TIME[CAR[N]],OUTOF[N],MIL[CAR[N]],
        AVG[CAR[N]],TWAIT[CAR[N]]),LIST5(A100,ATOTL,PLAT,PASS,MEAN,VAR);
FORMAT ASZ(S120,A1.0) ,
       FORM1(" FINISH  CAR  INTERARRIVAL   EXIT   DESIRED  AVERAGE",
            "  TIME",A1.0,"POSITION  NR      TIME      HEADWAY  ",
            "SPEED    SPEED  DELAYED",A1.0,
            X17,"-SECS-     -SECS-    -MPH-     -MPH-    -SECS-",A1.2),
       F1(X3,I3,X2,I3,X7,D4.1,X7,D4.1,X4,D4.1,X4,D4.1,X4,I4,A1.0),
       F2(X4,"-",X4,"-",X8,I3,X8,I3,X5,D4.1,X4,D4.1,X4,I4,A1.5),
       FORM5("AVERAGE DELAY FOR ALL CARS = ",I5," SECONDS",A5.2,
            "AVERAGE DELAY FOR THOSE DELAYED = ",I5," SECONDS",A1.2,
            "AVERAGE PLATOON SIZE = ",D5.2," CARS",A1.2,
            "AVERAGE NUMBER OF PASSES PER VEHICLE = ",D5.2,A1.2,
            "MEAN INTERARRIVAL TIME = ",I4," SECONDS",A1.2,
            "VARIANCE = ",I5,A1.5);
    NEXT= 15; CLOK2=1; M=(2**11)-1; RI=13579; R=(2**5.5)+3;
    PX[0]=16000;
    FOR N=(1,1,8) DO PX[N]=PX[N-1]+200 ;

          VALUES OF INDEPENDENT VARIABLES.

    MU=88;DEV=8.8;B1=6;C5=1.7;
    C1=1.0;C2=C3=0.5;C4=0.3;C6=.25 ;
    DENSITY=MU*(B1+0.5);

          CHECK TO SEE IF ARRIVAL IS DUE.
```

```
BOOK: CLOCK=MIN(CLOK1,CLOK2);
    IF CLOCK EQL CLOK1 THEN GO TO ARVL ELSE GO TO CHECK;

          ASSIGNMENT OF DESIRED SPEED TO CURRENT ARRIVAL.

ARVL:IF J EQL 200 THEN BEGIN CLOCK=CLOK2; GO TO CHECK END;
    J=J+1; CAR[J]=J; ENTRY[J]=CLOCK;
    FOR N=(1,1,12) DO BEGIN
     RI=MOD(R*RI,M); RN=RI/M ; NORM=NORM+RN END;
    NORM=NORM-6;
    DES[J]=MU+NORM*DEV; MIL[J]=DES[J]*(3600/5280); NORM=0;
    IF TIME[J] LSS 3 AND J GTR 1 AND DES[J] LSS ACT[J-1] THEN
     ACT[J]=DES[J]-0.5*(DES[J]-ACT[J-1])ELSE ACT[J]=DES[J];
    RI=MOD(R*RI,M); RN=RI/M;

          ASSIGNMENT OF ARRIVAL TIME FOR NEXT ARRIVAL.

    CLACK=0.5-B1*LN(RN);
    TIME[J+1]=CLACK;
    CLOK1=CLOK1+CLACK;
    GO TO BOOK;

          BEGIN UPDATING OF SPEEDS FOR ALL CARS.

CHECK: IF CLOCK EQL NEXT THEN BEGIN

          ROUTINE TO GENERATE TRACE OF NUMBER OF CARS PAST POINTS ON ROAD.

        I=I+1;
        FOR F=(1,1,8) DO BEGIN
         FOR S=(1,1,J) DO XT[F]=XT[F]+PT[F,S];
         AX[F,I]=XT[F]; XT[F]=0 END;
        NEXT=NEXT+10 END;
       N=J+1;

          EXAMINE NEXT CAR IN LINE.
```

```
SIP: N=N-1;C=CAR[N];

          ROUTINE TO TRACE SPEED OF SELECTED VEHICLE.

     IF C EQL 100 THEN BEGIN
      IF MOD(CLOK2,2) EQL 0 THEN BEGIN
       V=ENTIER((CLOK2-ENTRY[C])/2); SPD[V]=ACT[C] END; END;

          ROUTINE TO FIND WHICH CAR IS AHEAD OF THE CAR NOW BEING EXAMINED.

     IF BI+2 GEQ N THEN K=CAR[N-1] ELSE
     IF FLAP[CAR[N-1]] EQL 0 THEN K=CAR[N-1] ELSE
     IF DIST[CAR[N-2]]-DIST[CAR[N-1]] GTR 0 THEN K=CAR[N-1] ELSE
     K=CAR[N-2];

          DECREMENT WAITING TIME OF CAR[N].

     DECISION[C]=DECISION[C]-0.5 ; WAIT[C]=WAIT[C]-0.5;
     IF DIST[C] GEQ 37000 THEN GO TO TELL ELSE GO TO SEE ;

          CAR[N] HAS TRAVELED SEVEN MILES:  COMPUTE STATISTICS.

TELL:IF N EQL 1 THEN CLICK = CLOK2;
     DIST[C]=DIST[C]+1000 ;
     THRU[C]=CLOK2-ENTRY[C];
     AVG[C]=(37000*360)/(THRU[C]*528);
     OUTOF[N]=CLOK2-CLICK;
     BI=BI+1; CLICK=CLOK2;
     FLIP[C]=FLIP[K]=FLAP[C]=WAIT[C]=WAIT[K]=DANGER[C]=DANGER[K]=0;
     IF C EQL 100 THEN OUTA=CLOK2;
     IF BI EQL 200 THEN GO TO RELAX ELSE GO TO GEE;

          ALL CARS TO BE EXAMINED ARE OUT OF SYSTEM:
          PRINT STATISTICS AND TRACES.

RELAX: WRITE(FORM1);
```

```
FOR N=(1,1,200) DO WRITE(LIST1,F1);
FOR N=(1,1,120) DO A[N]=" ";
FOR N=(1,1,80) DO A[N] ="-";
WRITE(A,ASZ);
FOR N=(1,1,200) DO BEGIN
       N1=N1+TIME[N]/200;
       N2=N2+OUTOF[N]/200;
       N3=N3+MIL[N]/200;
       N4=N4+AVG[N]/200 END;
WRITE(LS,F2);
FOR N=(1,1,200) DO BEGIN
 TUNIT=TUNIT+UNIT[N];
 TOTEL=TOTEL+TWAIT[N] END;
ATOTL=TOTEL/TUNIT;
A100=TOTEL/200;
PLAT=PLAT/NUM;
MEAN=N2;
PASS=PASS/200;
FOR N=(1,1,200) DO VAR=VAR+(MEAN-OUTOF[N])**2/200 ;
WRITE(LIST5,FORM5);
FOR F=(1,1,I) DO BEGIN
 FOR L=(1,1,120) DO A[L]=" ";
 IF MOD(F,5) EQL 0 THEN FOR L=(1,1,99) DO A[L]="-";
 FOR P=(1,1,8) DO BEGIN
  G=AX[P,F]+1;
  IF G GTR 100 THEN G=G-100;
  A[G]=P END;
 WRITE(ASZ,A) END;
V=ENTIER((OUTA-ENTRY[100])/2) ;
FOR K=(1,1,V) DO BEGIN
 FOR N=(1,1,120) DO A[N]=" ";
 G=ENTIER(SPD[K]*0.68) ;
 A[G]="." ;
 WRITE(A,ASZ) END;
GO TO ZOOM ;
```

```
          TERMINATE PROGRAM AT ADDRESS ZOOM.

GEE: IF BI+1 GEQ N THEN GO TO TERM1 ELSE GO TO SIP ;
SEE: IF BI+1 GEQ N THEN GO TO TERM1 ELSE GO TO MORE ;

          LEAD CAR:  UPDATE SPEED AND INCREMENT CLOCK.

TERM1: IF FLIP[C] EQL 0 THEN ACT[C]=MIN(DES[C],ACT[C]+1);
       DIST[C]=DIST[C]+0.5*ACT[C];
       CLOK2=CLOK2+0.5;
       IF CLOK2 EQL NEXT THEN BEGIN

          DETERMINE COUNT OF NUMBER OF CARS PAST POINTS ON ROAD.

        N=J+1;
KSIP:   N=N-1; F=Z=1; C=CAR[N];
        FOR F=F WHILE DIST[C] GEQ PX[Z] AND Z LEQ 8 DO BEGIN
          PT[F,N]=1 ; F=Z=F+1 END;
        IF N EQL 1 THEN GO TO STP ELSE GO TO KSIP ;
STP:    END;
       GO TO BOOK ;

          RETURN TO "BOOK" TO CHECK FOR NEW ARRIVAL.


          DATA RELEVANT TO PASSING REQUIREMENTS:

MORE:  CT=ACT[C]*0.68 ;
       IF CT LSS 20 THEN BEGIN
         K1=1.20; T1=3.0; D2=65; GO TO L1 END;
       IF CT LSS 30 THEN BEGIN
         K1=1.18; T1=3.3; D2=100; GO TO L1 END;
       IF CT LSS 40 THEN BEGIN
         K1=1.16; T1=3.6; D2=140; GO TO L1 END;
       IF CT LSS 50 THEN BEGIN
         K1=1.14; T1=3.9; D2=180; GO TO L1 END;
       IF CT LSS 60 THEN BEGIN
```

```
      K1=1.12; T1=4.1; D2=240; GO TO L1 END;
    IF CT LSS 70 THEN BEGIN
      K1=1.10; T1=4.2; D2=280; GO TO L1 END;
    IF CT GEQ 70 THEN BEGIN
      K1=1.08; T1=4.3; D2=300; GO TO L1 END;
L1:  IF ACT[C]-ACT[K] LSS 10 AND K1*ACT[C]-ACT[K] NEQ 0 THEN
      T2=(DIST[K]-DIST[C]+ACT[C])/(K1*ACT[C]-ACT[K]) ELSE BEGIN
       T2=(DIST[K]-DIST[C]+ACT[C])/(ACT[C]-ACT[K]); K1=1.0 END;
     D1=ACT[C]*K1*T2;
     D3=2*D2/3 ;
     SAFEGAP=D1+D2+D3;
     IF DIST[K]-DIST[C] EQL 0 THEN DENOM=1 ELSE DENOM=DIST[K]-DIST[C];
     ACL=C2*ACT[C]*(ACT[K]-ACT[C])/DENOM**2 ;
     CHOICE=MIN(DES[C],ACT[C]+ACL) ;
     IF DIST[K]-DIST[C] LSS 0.7*ACT[C] AND ACT[C] GEQ ACT[K] THEN
      CT=ACT[C]+C3*MIN(ACT[K]-ACT[C],-4) ELSE
     IF ACT[C] GTR ACT[K] THEN CT=ACT[C]+C4*(ACT[K]-ACT[C]) ELSE
     CT=MIN(DES[C],ACT[C]+1) ;
     IF WAIT[C] GTR 0 AND FLIP[C] EQL 0 OR DECISION[C] GTR 0 THEN
      TWAIT[C]=TWAIT[C]+0.5;
     IF DECISION[C] GTR 0 THEN BEGIN
       ACT[C]=CT; DIST[C]=DIST[C]+0.5*ACT[C];
       GO TO SIP END ;
     IF WAIT[C] LEQ 0 THEN BEGIN FLIP[C]=0; GO TO TEST END;
     IF WAIT[C] GTR 0 THEN BEGIN
       IF FLIP[C] EQL 0 THEN BEGIN

          WAITING TO PASS:  UPDATE SPEED.

         ACT[C]=CT; DIST[C]=DIST[C]+0.5*ACT[C];
         GO TO SIP END ;
       IF FLAP[C] EQL 1 THEN BEGIN
         IF BI+2 GEQ N THEN BEGIN

          PASSING:  NOT IN DANGER:  MAINTAIN SPEED.
```

```
  DIST[C]=DIST[C]+0.5*ACT[C];
  GO TO SIP END ;
IF FLAP[CAR[N-2]] EQL 0 THEN Z=CAR[N-2] ELSE BEGIN
  IF DIST[CAR[N-3]]-DIST[CAR[N-2]] GTR 0 THEN Z=CAR[N-2]
  ELSE Z=CAR[N-3] END ;
IF DIST[Z]-DIST[C] GEQ ACT[C] THEN BEGIN

 PASS COMPLETE:  NOT IN DANGER:  CHANGE POSITION INDICES
 AND UPDATE SPEED.

  IF DIST[C]-DIST[K] GEQ ACT[C] THEN BEGIN
    DIST[K]=DIST[K]+0.5*ACT[C];
    PASS=PASS+1 ;
    CAR[N]=K ; CAR[N-1]=C ; DANGER[C]= DANGER[K]=0;
    WAIT[C]=WAIT[K]=FLIP[C]=FLIP[K]=FLAP[C]=0 ;
    GO TO SIP END ELSE BEGIN

 PASSING:  NOT IN DANGER : MAINTAIN SPEED.

    DIST[C]=DIST[C]+0.5*ACT[C];
    GO TO SIP END; END;

 PASSING:  IN DANGER:  CHANGE POSITION INCICES IF AHEAD OF
 CAR BEING PASSED AND UPDATE SPEED.

IF DIST[K]-DIST[C] GEQ 0 THEN BEGIN
  WAIT[C]=WAIT[K]=FLIP[C]=FLIP[K]=0;
  DANGER[C]=1;
  ACT[C]=CT ;
  DIST[C]=DIST[C]+0.5*ACT[C];
  GO TO SIP END ELSE BEGIN
  PASS=PASS+1; DANGER[K]=1;
  IF ACT[Z] LSS ACT[C] THEN ACT[C]=ACT[C]-.5*(ACT[C]-ACT[Z]) ;
  ACT[K]=MIN(ACT[C]-2,ACT[K]-2);
  DIST[K]=DIST[K]+0.5*ACT[K];
  WAIT[C]=WAIT[K]=FLIP[C]=FLIP[K]=FLAP[C]=0 ;
  CAR[N]=K; CAR[N-1]=C ; GO TO SIP END END ELSE
```

```
         BEING PASSED:  MAINTAIN SPEED UNLESS PASSING CAR IS IN DANGER.

          IF BI+2 LSS N THEN BEGIN
            IF FLAP[CAR[N-1]] EQL 0 THEN Z=CAR[N-1] ELSE BEGIN
              IF DIST[CAR[N-2]]-DIST[CAR[N-1]] GTR 0 THEN Z=CAR[N-1]
              ELSE Z=CAR[N-2] END;
            IF DIST[Z]-DIST[C] LSS 1.4*ACT[C] THEN ACT[C]=ACT[C]-2 ;
            DIST[C]=DIST[C]+0.5*ACT[C]; GO TO SIP END ELSE BEGIN
            DIST[C]=DIST[C]+0.5*ACT[C]; GO TO SIP END END ;
TEST:   IF WAIT[C] LEQ 0 AND FLAP[C] EQL 1 THEN BEGIN

         PASS COMPLETE:  CHANGE POSITION INDICES AND UPDATE SPEED.

        DANGER[C]=DANGER[K]=0;
        PASS=PASS+1 ;
        WAIT[C]=WAIT[K]=FLIP[C]=FLIP[K]=FLAP[C]=0 ;
        DIST[K]=DIST[K]+0.5*ACT[K];
        CAR[N]=K ; CAR[N-1]=C ;
        GO TO SIP END ;
EXAM:   IF DIST[K]-DIST[C] GEQ 3*ACT[C] THEN BEGIN

         NOT FOLLOWING NEXT CAR:  UPDATE SPEED.

        ACT[C]=MIN(ACT[C]+1,DES[C]) ;
        DIST[C]=DIST[C]+0.5*ACT[C] ;
        PLAT=PLAT+PLAT1; PLAT1=1; NUM=NUM+1 ;
        GO TO SIP END ;
      IF DANGER[K] EQL 1 THEN BEGIN DANGER[K]=0 ; FACT=1.1 END
      ELSE FACT=0.9;
      IF DIST[K]-DIST[C] GEQ 20+FACT*ACT[C] THEN BEGIN

         FOLLOWING NEXT CAR BUT NOT PLATOONED WITH IT:  UPDATE SPEED.

        ACT[C]=CHOICE ; DIST[C]=DIST[C]+0.5*ACT[C];
        PLAT=PLAT+PLAT1; PLAT1=1; NUM=NUM+1 ;
```

```
            GO TO SIP END ;
TRY: PLAT1=PLAT1+1;

             PLATOONED: IF NEXT CAR IS NOT WAITING TO PASS, THEN
             MAKE DECISION (SEE BELOW) TO PASS, OTHERWISE UPDATE SPEED.

     IF WAIT[K] LEQ 0 THEN GO TO RULE ;
     WAIT[C]=WAIT[K]-0.5;
     UNIT[C]=1; ACT[C]=CT ; DIST[C]=DIST[C]+0.5*ACT[C];
     GO TO SIP ;

             PASSING CRITERIA:

RULE:  IF DES[C] LSS 1.05*ACT[K] THEN BEGIN
         ACT[C]=CT ; WAIT[C]=T1; UNIT[C]=1 ;
         DIST[C]=DIST[C]+0.5*ACT[C] ;
         GO TO SIP END ;
      IF BI  +2 GEQ N THEN GO TO RID ;
       IF FLAP[CAR[N-2]] EQL 0 THEN Z=CAR[N-2] ELSE BEGIN
         IF DIST[CAR[N-3]]-DIST[CAR[N-2]] GTR 0 THEN Z=CAR[N-2]
         ELSE Z=CAR[N-3] END ;
       IF DIST[Z]+ACT[Z]*T2 LEQ DIST[C]+D2+2*ACT[C] THEN BEGIN
         ACT[C]=CT; DIST[C]=DIST[C]+0.5*ACT[C] ; UNIT[C]=1 ;
         DECISION[C]=T1;
         GO TO SIP END ;
RID: RI=MOD(R*RI,M); RN=RI/M;
     IF RN LSS C6 THEN GO TO CANT ;
     RI=MOD(R*RI,M); RN=RI/M;
     GAP= -C5*RN*DENSITY ;
     V28=GAP/SAFEGAP ;
     IF V28 GEQ C1 THEN GO TO FLY ;

             PASSING CRITERIA NOT MET:  UPDATE SPEED.

CANT: ACT[C] = CT ;
      WAIT[C]= MAX(GAP/(ACT[C]+MU),T1) ;
      DIST[C]=DIST[C]+0.5*ACT[C];
```

```
       UNIT[C]=1;
       GO TO SIP ;

           PASSING CRITERIA MET:  ASSUME AVERAGE PASSING SPEED.

FLY:   ACT[C]=K1*ACT[C] ;
       WAIT[C]=T2;
       WAIT[K]=T2+0.5 ;
       FLIP[C]=FLIP[K]=FLAP[C]=0 ;
       DIST[C]=DIST[C]+0.5*ACT[C];
       DECISION[C]=DECISION[K]=0 ;
       GO TO SIP ;
ZOOM:  END OF PROGRAM ;

           TERMINATE PROGRAM.
```

Typical Output Data

Mean Desired Speed = 60 mph

Mean Arrival Headway = 6.5 seconds

Mean Opposing Headway = 6.5 seconds

FINISH POSITION	CAR NR	INTERARRIVAL TIME -SECS-	EXIT HEADWAY -SECS-	DESIRED SPEED -MPH-	AVERAGE SPEED -MPH-	TIME DELAYED -SECS-
1	1	0.0	0.0	65.9	65.7	0
2	2	7.0	1.0	68.7	66.7	230
3	3	.9	47.0	59.6	59.5	4
4	4	.7	.5	63.8	59.5	376
5	5	2.6	19.5	57.3	57.2	0
6	6	2.0	1.5	59.1	57.3	364
7	7	8.7	1.0	68.7	58.3	304
8	8	6.7	1.0	64.3	59.1	275
9	9	2.0	9.0	58.3	58.1	0
10	10	2.3	18.0	56.1	56.1	0
11	11	1.3	1.0	60.4	56.1	395
12	12	5.0	1.5	63.8	56.6	322
13	13	12.8	45.5	52.7	52.7	0
14	14	7.2	1.0	65.5	53.4	396
15	15	2.7	1.0	60.5	53.6	323
16	16	7.9	16.0	52.7	52.7	0
17	17	7.2	1.0	65.5	53.4	399
18	18	2.7	1.0	60.5	53.6	328
19	19	7.9	1.0	56.1	54.3	215
20	20	1.3	1.0	63.9	54.4	382
21	21	1.6	1.5	57.3	54.4	353
22	22	2.0	1.0	59.1	54.5	358
23	23	8.7	1.0	64.7	55.4	333
24	24	8.1	32.0	52.7	52.7	0
25	25	7.2	1.0	64.7	53.4	397
26	26	8.1	1.0	56.1	54.2	205
27	27	1.3	1.0	63.9	54.2	410
28	28	1.6	1.0	57.3	54.3	328
29	29	2.0	16.0	52.7	52.7	0
30	30	7.2	1.0	65.5	53.4	399
31	31	1.0	1.0	56.5	53.4	308
32	32	8.9	1.0	63.8	54.3	358
33	33	12.8	1.5	61.3	55.6	228
34	34	12.1	31.5	53.4	53.4	0
35	35	15.8	1.0	63.9	55.1	340
36	36	1.6	1.0	63.8	55.2	294
37	37	12.8	1.0	57.4	56.6	73
38	38	23.3	50.5	53.4	53.4	0
39	39	15.8	1.0	60.4	55.1	309
40	40	2.6	17.5	53.4	53.3	0
41	41	15.8	1.0	60.4	55.1	309
42	42	2.6	1.0	57.4	55.3	183
43	43	23.3	45.5	52.7	52.7	0
44	44	7.2	1.0	59.1	53.4	376
45	45	8.7	1.0	57.0	54.3	228
46	46	8.1	1.5	57.0	55.0	178
47	47	8.1	25.0	53.1	53.1	0
48	48	2.1	1.0	63.0	53.2	417
49	49	8.8	1.5	65.5	54.0	333
50	50	1.0	9.5	53.1	53.1	4
51	51	2.1	1.0	67.1	53.2	418
52	52	4.1	1.5	56.9	53.5	324
53	53	4.6	1.0	57.3	53.9	333

54	54	2.0	1.0	64.3	54.0	367
55	55	8.6	1.0	64.1	54.9	340
56	56	12.9	1.0	65.5	56.4	256
57	57	2.7	1.0	56.9	56.6	23
58	58	4.6	1.0	57.4	57.0	21
59	59	23.3	1.0	67.1	60.1	258
60	60	4.1	1.0	61.0	60.5	20
61	61	4.9	16.0	59.1	58.9	0
62	62	8.7	1.0	65.5	60.0	313
63	63	2.7	32.0	56.1	56.1	0
64	64	1.3	1.0	65.5	56.1	397
65	65	2.7	1.0	63.5	56.3	337
66	66	13.0	1.5	66.9	57.8	323
67	67	12.4	9.0	58.4	58.3	0
68	68	1.8	2.5	58.3	58.2	0
69	69	2.3	1.0	66.9	58.4	376
70	70	12.4	1.0	60.4	59.9	53
71	71	2.6	1.0	61.0	60.2	219
72	72	4.9	29.0	57.0	56.9	0
73	73	8.1	1.0	63.9	57.8	337
74	74	1.6	38.0	53.4	53.4	0
75	75	15.8	1.0	65.5	55.1	348
76	76	2.7	23.5	52.7	52.7	0
77	77	7.2	1.0	64.3	53.4	396
78	78	8.6	1.0	56.5	54.3	208
79	79	8.9	1.0	64.7	55.2	357
80	80	8.1	1.0	59.1	56.1	163
81	81	8.7	1.0	64.1	57.0	315
82	82	12.9	49.5	52.7	52.7	0
83	83	7.2	1.0	65.5	53.4	399
84	84	2.7	1.0	56.5	53.6	286
85	85	8.9	1.0	64.7	54.5	363
86	86	8.1	1.5	58.4	55.3	188
87	87	1.8	.5	63.8	55.4	401
88	88	12.8	1.5	60.0	56.8	147
89	89	.7	.5	64.3	56.9	394
90	90	2.0	1.0	63.5	57.0	334
91	91	13.0	1.0	63.8	58.6	200
92	92	12.8	26.5	56.9	56.8	0
93	93	4.6	1.0	59.1	57.2	312
94	94	8.7	1.0	63.8	58.2	267
95	95	12.8	1.0	61.0	59.9	97
96	96	4.9	62.0	52.7	52.7	0
97	97	7.2	1.0	60.0	53.4	379
98	98	1.2	4.0	53.1	53.1	4
99	99	2.1	1.0	60.0	53.2	416
100	100	1.2	1.5	56.5	53.2	353
101	101	8.9	1.0	64.7	54.1	379
102	102	8.1	1.0	63.5	54.9	292
103	103	13.0	1.0	63.0	56.4	266
104	104	8.8	1.0	58.4	57.4	62
105	105	1.8	1.0	61.3	57.5	373
106	106	12.1	52.0	52.7	52.7	0
107	107	7.2	1.0	63.0	53.4	393
108	108	8.8	1.0	58.4	54.3	261
109	109	1.8	1.5	57.3	54.3	265
110	110	2.0	1.0	60.0	54.4	363
111	111	.7	1.0	57.3	54.4	260

112	112	2.0	1.0	64.3	54.5	373
113	113	8.6	1.0	59.1	55.4	230
114	114	8.7	1.0	57.3	56.4	69
115	115	2.0	1.0	63.9	56.5	385
116	116	1.6	1.0	56.9	56.6	21
117	117	4.6	2.0	57.0	56.9	0
118	118	8.1	1.0	65.5	57.8	347
119	119	1.0	14.5	56.1	56.1	4
120	120	1.3	1.0	65.5	56.1	397
121	121	1.0	1.5	56.5	56.1	309
122	122	8.9	1.0	57.3	57.1	43
123	123	2.0	1.0	63.0	57.2	373
124	124	8.8	1.0	66.9	58.2	300
125	125	12.4	1.0	60.8	59.8	74
126	126	20.0	16.5	60.4	60.3	0
127	127	2.6	12.0	59.1	59.0	0
128	128	8.7	1.0	65.5	60.1	313
129	129	1.0	8.5	59.1	59.0	4
130	130	8.7	22.0	57.3	57.2	0
131	131	2.0	1.5	60.4	57.3	376
132	132	2.6	9.5	56.5	56.4	0
133	133	8.9	1.0	63.8	57.4	336
134	134	12.8	48.5	53.1	53.1	0
135	135	2.1	1.0	65.5	53.2	418
136	136	1.0	1.5	56.9	53.2	364
137	137	4.6	1.0	59.1	53.6	380
138	138	8.7	1.0	64.1	54.5	314
139	139	12.9	1.0	57.0	55.9	107
140	140	8.1	1.0	63.8	56.8	329
141	141	12.8	43.5	53.1	53.1	0
142	142	2.1	1.0	63.8	53.2	415
143	143	12.8	1.0	67.1	54.6	322
144	144	4.1	1.5	66.9	54.9	353
145	145	12.4	1.0	60.8	56.3	201
146	146	20.0	15.0	57.0	56.9	0
147	147	8.1	37.5	53.4	53.4	0
148	148	15.8	1.0	57.4	55.1	228
149	149	23.3	1.0	60.4	57.9	119
150	150	2.6	1.0	67.1	58.1	369
151	151	4.1	1.0	64.3	58.6	275
152	152	8.6	21.0	57.0	56.9	0
153	153	8.1	1.0	63.0	57.8	329
154	154	8.8	5.5	58.4	58.3	0
155	155	1.8	1.0	61.3	58.4	377
156	156	12.1	59.0	52.7	52.7	0
157	157	7.2	1.0	66.9	53.4	401
158	158	12.4	1.0	65.5	54.7	303
159	159	1.0	15.0	53.1	53.1	4
160	160	2.1	1.0	65.5	53.2	418
161	161	1.0	1.5	59.1	53.1	367
162	162	8.7	1.0	57.3	54.0	321
163	163	2.0	1.0	63.5	54.1	367
164	164	13.0	1.0	60.8	55.5	273
165	165	20.0	1.0	63.8	58.0	183
166	166	12.8	22.0	56.9	56.8	0
167	167	4.6	7.5	56.5	56.4	0
168	168	8.9	1.0	65.5	57.4	347
169	169	1.0	40.5	52.7	52.7	4

170	170	7.2	1.0	60.4	53.4	384
171	171	2.6	1.0	56.1	53.5	277
172	172	1.3	1.0	64.7	53.6	416
173	173	8.1	1.5	56.1	54.3	183
174	174	1.3	.5	63.0	54.4	411
175	175	8.8	1.0	60.0	55.4	263
176	176	.7	1.0	64.3	55.3	404
177	177	2.0	.5	67.1	55.5	347
178	178	4.1	1.0	58.4	55.9	174
179	179	1.8	1.0	63.8	56.0	375
180	180	12.8	2.5	57.4	57.3	0
181	181	23.3	1.0	64.3	60.3	209
182	182	2.0	33.5	56.1	56.1	0
183	183	1.3	1.0	65.5	56.1	397
184	184	1.0	1.5	56.5	56.1	310
185	185	8.9	1.0	64.7	57.1	344
186	186	8.1	9.5	57.0	56.9	0
187	187	8.1	1.0	63.0	57.8	329
188	188	8.8	19.5	56.5	56.4	0
189	189	8.9	1.0	64.7	57.5	342
190	190	8.1	12.5	57.0	56.9	0
191	191	8.1	1.0	60.4	57.8	284
192	192	2.6	9.5	57.0	56.9	0
193	193	8.1	1.0	65.5	57.8	347
194	194	2.7	10.5	56.9	56.8	0
195	195	4.6	8.0	56.5	56.4	0
196	196	8.9	1.0	68.7	57.4	360
197	197	.8	1.0	58.3	57.4	161
198	198	2.3	1.0	65.5	57.5	379
199	199	2.7	14.0	56.1	56.1	0
200	200	1.3	1.0	60.0	56.1	399
-	-	7	7	60.3	55.8	

AVERAGE DELAY FOR ALL CARS = 219 SECONDS

AVERAGE DELAY FOR THOSE DELAYED = 287 SECONDS

AVERAGE PLATOON SIZE = 1.21 CARS

AVERAGE NUMBER OF PASSES PER VEHICLE = 0.00

MEAN INTERARRIVAL TIME = 7 SECONDS

VARIANCE = 166

APPENDIX B

SUMMARIZED DATA AND ANALYSIS OF VARIANCE TESTS

SUMMARIZED DATA

Mean Desired Speed (mph)	Mean Arrival Headway (secs)	Mean Opposing Headway (secs)	Average Speed (mph)	Average Platoon Size	Passes per Vehicle	Mean Exit Headway (secs)
60	6.5	6.5	55.8	1.38	0.00	6
		13.0	55.9	1.23	.06	6
	12.5	12.5	57.1	1.14	.02	13
		25.0	58.7	1.04	1.35	13
	18.5	18.5	59.3	1.04	.78	16
		37.0	59.7	1.02	.90	18
50	6.5	6.5	45.8	1.48	0.00	7
		13.0	46.1	1.26	.37	7
	12.5	12.5	47.9	1.18	.02	13
		25.0	49.6	1.05	1.42	17
	18.5	18.5	49.7	1.03	.99	18
		37.0	49.9	1.02	1.18	16
40	6.5	6.5	37.2	1.43	0.00	7
		13.0	38.0	1.21	.96	7
	12.5	12.5	38.4	1.17	.44	13
		25.0	38.9	1.04	1.81	14
	18.5	18.5	39.6	1.06	1.55	17
		37.0	39.8	1.04	1.43	18
30	6.5	6.5	27.1	1.64	0.00	7
		13.0	27.9	1.15	3.80	7

SUMMARIZED DATA (Concluded)

Mean Desired Speed (mph)	Mean Arrival Headway (secs)	Mean Opposing Headway (secs)	Average Speed (mph)	Average Platoon Size	Passes per Vehicle	Mean Exit Headway (secs)
30	12.5	12.5	28.8	1.12	1.59	13
		25.0	29.6	1.08	2.27	12
	18.5	18.5	29.8	1.05	1.86	17
		37.0	29.9	1.05	1.78	19
20	3.5	3.5	16.5	3.59	0.01	5
		7.0	17.8	2.57	0.37	5
	6.5	6.5	18.4	1.84	0.00	8
		13.0	18.9	1.18	6.58	8
	12.5	12.5	19.6	1.10	3.25	14
		25.0	19.8	1.12	3.54	14
	18.5	18.5	19.9	1.06	2.38	20
		37.0	19.9	1.06	2.74	20
15	3.5	3.5	11.6	3.23	0.06	5
		7.0	12.5	2.41	0.62	4

Analysis of Variance Tests

In the following ANOVA formulations, the desired speed level will be given by "A", the mean arrival headway will be given by "B", and the relative opposing headway will be given by "C". Error was chosen to be composed of the third order interaction term and is represented by E. Each ANOVA is for the three factor design, unless otherwise noted. The first table shows the critical F values for three different levels of significance.

F Values for Three Factor Experiment

Source	df	$F_{.01}$	$F_{.05}$	$F_{.10}$
A	4	7.01	3.84	2.81
B	2	8.65	4.46	3.11
C	1	11.30	5.32	3.46
AB	8	6.03	3.44	2.59
AC	4	7.01	3.84	2.81
BC	2	8.65	4.46	3.11
E	8	--	--	--

ANOVA for Average Speed

Source	MS	F	Significant (*,%)
A	1353	27.62	*,1%
B	21	0.43	--
C	2	0.04	--
AB	2	0.04	--
AC	1	0.02	--
E	49	--	--

ANOVA for Average Speeds (Two Factor)

Desired Speed	Source	MS	F	$F_{.10}$	Significant *,%
	B	1.50	9.3	9.00	*,10
20 mph	C	0.17	1.0	8.54	--
	E	0.17	--	--	--
	B	3.50	21.8	9.00	*,5
30 mph	C	0.67	4.0	8.54	--
	E	0.17	--	--	--
	B	3.16	19.7	9.00	*,5
40 mph	C	0.67	4.0	8.54	--
	E	0.17	--	--	--
	B	8.53	17.6	9.00	*,10
50 mph	C	1.00	2.0	8.54	--
	E	0.50	--	--	--
	B	8.67	12.9	9.00	*,10
60 mph	C	0.67	1.0	8.54	--
	E	0.67	--	--	--

ANOVA for Average Platoon Size

Source	MS	F	Significant
A	0.006	0.86	--
B	0.322	46.00	*,1%
C	0.150	21.43	*,1%
AB	0.007	1.00	--
AC	0.005	0.71	*,1%
BC	0.084	12.00	*,1%
E	0.007	--	--

ANOVA for Average Number of Passes per Vehicle

Source	MS	F	Significant
A	5.44	4.39	*,5%
B	0.72	0.58	--
C	5.38	4.33	*,10%
AB	0.30	0.24	--
AC	2.03	1.64	--
BC	4.57	3.28	*,10%
E	1.24	--	--

Generation of Random Numbers

The multiplicative congruential method was used to generate random numbers. Sequences of non-negative integers were generated by the recurrence relation

$$RI_{i+1} = RI_i \cdot R (\text{Mod } M)$$

from whence the random number was easily obtained as follows.

$$RN_{i+1} = RI_{i+1}/M$$

It is necessary only to specify the initial random integer, RI, and the values of R and M. For computation on the Univac 1108, the following values were chosen.

$$RI_1 = 13579$$

$$R = 2^{5.5} + 3$$

$$M = 2^{11} - 1$$

LITERATURE CITED

1. Andreassand, D. C., "The Use of a Mathematical Description of Vehicle Performance to Determine Overtaking Time and Distances," Proceedings, Third Conference, Australian Road Research Board, Vol. 3, Part 1, Sydney, Australia, 1966, pp. 518-537.

2. Buckley, D. J., "Road Traffic Headway Distributions," Australian Road Research Board, Vol. 1, Sydney, Australia, 1962, pp. 153-187.

3. Daou, A., "On Flow Within Platoons," Australian Road Research Board, Vol. 2, No. 7, pp. 4-13, 1962.

4. Edie, L. C., "Car-following and Steady State Theory for Noncongested Traffic," Operations Research 9:1, 68-70 (Jan.-Feb. 1961).

5. Erlander, S., "A Mathematical Model for Traffic on a Two-lane Road," Vehicular Traffic Science, Elsivier Publishing Company, New York, 1967, pp. 138-152.

6. Gerlough, D. L., "Traffic Inputs for Simulation on a Digital Computer," Proc., Highway Research Board, 38, 1959.

7. Gervais, E. F., "National Proving Ground for Freeway Surveillance Control and Electronic Traffic Aids," Proceedings, Program Preview Meeting, Bureau of Public Roads, Dec. 1966, pp. 298-309.

8. Glanville, W. H., Research on Road Traffic, J. W. Arrowsmith Ltd., Bristol, 1965, p. 178.

9. Greenberg, H., "A Mathematical Analysis of Traffic Flow," Tunnel Traffic Capacity Study, The Port of New York Authority, New York, 1958.

10. Greenshields, B. D., "A Study of Traffic Capacity," Highway Research Board Proceedings, 14, 1934, pp. 448-474.

11. Gustavsson, J., "A Model for Overtaking on a Two-lane Road with Limited Visibility," Vehicular Traffic Science, Elsevier Publishing Company, New York, 1967, pp. 138-152.

12. Herman, R., Montroll, E., Potts, R. B., and Rothery, R. W., "Traffic Dynamics: Analysis of Stability in Car-Following," Operations Research 7, 86-106 (1959).

LITERATURE CITED (Continued)

13. Herman, R. and Potts, R. B., "Single-lane Traffic Theory and Experiment," Theory of Traffic Flow, Elsevier Publishing Company, New York, 1961, pp. 120-146.

14. Hobbs, R. D. and Richardson, B. D., Traffic Engineering, Pergamon Press, Oxford, 1967, pp. 21-32.

15. Keefer, L. E., "Are Transportation Studies Worth While?" Traffic Engineering and Control, 7:1, 42.

16. Levine, W. S. and Athans, M., "A Design Principle for Linear Feedback Control of the Position and Velocity of Vehicles within a Platoon of High Speed Vehicles," IEEE Transactions on Automatic Control, No. 3, 1968, pp. 355-362.

17. Lighthill, M. S. and Whitham, G. B., "On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads," Proceedings, Royal Statistical Society, Series B, No. 23, 1961, pp. 64-75.

18. Miller, R. L., "A Model for Traffic Flows on a Two-lane Two-way Rural Highway," Technical Report No. 20, Operations Research Center, MIT, Cambridge, June 1966, AS-634.597.

19. Naylor, T. H., Balintty, J. L., Burdick, D. S., and Chu, K., Computer Simulation Techniques, John Wiley and Sons, New York, 1966, pp. 85-97.

20. Oliver, R. M., "A Two-Lane Traffic Model," Operations Research Center, College of Engineering, University of California, Berkeley, February 1965.

21. Prisk, C. W., "Passing Practices on Rural Highways," Highway Research Board Proceedings, 1941, pp. 367-378.

22. Raff, M. S., "The Distribution of Blocks in an Uncongested Stream," Journal of the American Statistical Association, 46, 114-123 (1951).

23. Richards, P. I., "Shock Waves on the Highway," Operations Research, 4:1.

24. Ritter, L. and Paquette, R. J., Highway Engineering, The Ronald Press, New York, 1960, p. 151.

25. Theeden, T., "Convergence and Invariance Questions for Road Traffic with Free Overtaking," Vehicular Traffic Science, Elsevier Publishing Company, New York, 1967, p. 168.

LITERATURE CITED (Concluded)

26. Thorne, Shelia M., "Relative Effect of Buses and Cars on the Speed of Traffic," Traffic Engineering and Control, 7:2, 140-141 (1965).

27. Warnshuis, P., "Simulation of Traffic on an Isolated Two-lane Road," Transportation Research, 1, 75-83 (1967).

28. Yeo, G. F., "Traffic Delays on a Two-lane Road," Biometrica, 51, Parts 1/2, 11-15 (1964).